

Wideband noise characteristics of a lead-salt diode laser: possibility of quantum noise limited TDLAS performance

Peter Werle, Franz Slemr, Manfred Gehrtz, and Christof Bräuchle

The wideband noise characteristics of a PbEuSe molecular beam epitaxy diode laser have been measured up to 500 MHz. The cutoff of the frequency dependent ($1/f$ type) laser noise contribution was found to be 170 MHz for this particular laser. Above this cutoff frequency the photon shot noise dominates, as was demonstrated. A noise reduction of more than 2 orders of magnitude was observed in the shot noise limited domain when compared with the $1/f$ noise dominated region below 1 MHz. This finding indicates that a similar 2 orders of magnitude sensitivity improvement can be achieved in tunable diode laser absorption spectroscopy when frequency modulation techniques are applied instead of the more conventional derivative modulation below 1 MHz.

I. Introduction

Lead-salt diode lasers emitting in the mid-infrared region have become increasingly important for high sensitivity absorption spectroscopy,^{1,2} particularly in the monitoring of atmospheric trace gases.^{3,4} In most of the tunable diode laser absorption spectrometers (TDLAS) a conventional derivative modulation technique has been used leading to an optical density detection limit of the order of 10^{-5} with spectra averaged over a few seconds.^{3,5} Although this sensitivity is adequate for many uses, monitoring of some trace gases in clean air requires still higher sensitivity or detection speed. In attempting to improve the sensitivity and the detection speed of the present TDLAS instruments, the application of frequency modulation (FM) techniques has attracted increasing attention.⁶⁻¹¹

Frequency modulation is a relatively new spectroscopic technique¹² that permits quantum limited sensitivity to be attained.¹³ To achieve this ultimate sensitivity limit, the modulation frequency has to be selected sufficiently high, i.e., beyond the cutoff of the laser source noise. Both the amplitude and the fre-

quency characteristics of this excess noise depend on the laser used.

The noise characteristics of a ring dye laser operated in the visible region were reported by Hall *et al.*¹⁴ They found a noise reduction of more than 80 dB at modulation frequencies beyond 2 MHz when compared with a low frequency of 10 kHz. In appropriate experimental conditions, this noise reduction translates into an increased detection sensitivity of 10^4 . Wong and Hall¹⁵ demonstrated the quantum limited performance of a He-Ne laser absorption spectrometer with external modulation by an electrooptic modulator. Also, with the near-infrared GaAlAs laser diodes, frequency modulated by injection current modulation,¹⁶⁻¹⁸ near quantum limited sensitivity could be achieved at modulation frequencies around 250 MHz.¹⁹

However, for most of the atmospheric species lead-salt tunable diode lasers emitting in the 3-30- μm region have to be used. For this type of laser, Gehrtz *et al.*⁶ demonstrated that FM can also be achieved by directly modulating the injection current. So far, little is known about the noise characteristics of the lead-salt diode lasers and, therefore, the potential sensitivity improvement using FM techniques is uncertain. Previous work²⁰ was limited to a low frequency region up to 200 kHz which is not sufficient to evaluate the potential sensitivity improvement by going to modulation frequencies of the order of hundreds of megahertz.

In this work we report on wideband noise measurements up to a frequency of 500 MHz with a lead-salt diode laser. We identify the laser source cutoff frequency and demonstrate that the noise with frequencies above this cutoff is dominated by the fundamental

M. Gehrtz is with IBM Germany, Plant Mainz Laboratories, P.O. Box 2540, D-6500 Mainz, Federal Republic of Germany; C. Bräuchle is with University of Munich, Institute for Physical Chemistry, 11 Sophienstr., D-8000 Munich, Federal Republic of Germany; the other authors are with Fraunhofer Institute for Atmospheric Environment Research, 19 Kreuzteckbahnstr., D-8100 Garmisch-Partenkirchen, Federal Republic of Germany.

Received 18 July 1988.

0003-6935/89/091638-05\$02.00/0.

© 1989 Optical Society of America.

photon shot noise. The noise reduction in this quantum limited regime relative to that of the presently used low modulation frequencies is evaluated. The measurements indicate that the detection sensitivity can be improved by more than a factor of 100 using FM instead of the common derivative technique.

II. Noise Considerations

The sensitivity of a spectrometer depends on the achievable signal-to-noise ratio (SNR). If one dissects noise according to its various contributing sources the SNR can be described as

$$\text{SNR} = \frac{P_{\text{signal}}}{(P_{1/f}^2 + P_{sn}^2 + P_{tn}^2)^{1/2}}, \quad (1)$$

The major contributions to noise are the laser source noise, excess noise ($P_{1/f}$) in the detector, the detector shot noise (P_{sn}), and the detector thermal noise (P_{tn}). The laser source noise decreases with increasing frequency and because of this dependence it is often referred to as pink or $1/f$ noise. In contrast, the shot noise and the thermal noise do not depend on frequency and are said to have a white noise spectrum. Since the frequency and laser power dependence are the key for distinguishing the different noise sources, they are discussed here in more detail.

Thermal noise arises from the random velocity fluctuations (Brownian motion) of the charge carriers in a resistive material and it is often referred to as Johnson noise.²¹ The rms noise detector current is dependent on the absolute temperature T and is independent of the incident light power²²:

$$i_{\text{th}}^2 = 4k \frac{T}{R_{\text{eff}}} \Delta f. \quad (2)$$

In this equation k is the Boltzmann constant, Δf is the bandwidth of the measuring equipment, and R_{eff} is the effective detector load resistance.²³

Shot noise²⁴ originates from the discrete nature of photoelectron generation in a photodetector. Photons are generally Poisson distributed, and consequently, their random fluctuations are proportional to the square root of the radiation intensity. Taking into account the quantum efficiency η of the detector the rms shot noise detector current is²²

$$i_{\text{sn}}^2 = 2e \bar{i}_{dc} \Delta f, \quad (3)$$

with

$$\bar{i}_{dc} = e\eta \frac{P_{\text{laser}}}{h \cdot \nu},$$

where e is the electron charge, h is Planck's constant, ν is the light frequency, η is the detector quantum efficiency, and P is the incident light power. From this relation, the rms shot noise can be calculated if the incident light power is known.

The physical mechanism that produces $1/f$ noise is not well understood and no generally accepted mechanism for the generation of this noise has been proposed.²⁵ Several processes, such as contact noise, excess resistor noise, fluctuation of the work function, and laser source noise, may contribute to $1/f$ noise.²²

An experimentally measured relation for the $1/f$ rms noise detector current is²⁵

$$i_{1/f}^2 = c' \frac{i_{dc}^2}{f^b} \Delta f, \quad (4)$$

where c' is a detector constant, i_{dc} is the detector current, and b is typically 1 but can range between 0.8 and 1.5. Relation (4) shows that $1/f$ noise increases with increasing dc bias current. For photovoltaic detectors $1/f$ noise can be reduced by reducing i_{dc} . However, some dc bias current is necessary to achieve high frequency response from such detectors.

The varying dependence of the noise power contributions on dc current and thus on the laser power provides a tool for distinguishing between the different noise sources. While thermal noise is independent of i_{dc} , the shot noise power is proportional to i_{dc} , and the $1/f$ noise power is proportional to i_{dc}^2 . Therefore, attenuation of the laser beam intensity by a factor of 2 with a neutral density filter will decrease the source or excess noise level by 6 dB while an observed 3-dB noise reduction will demonstrate shot noise limited operation.

The $1/f$ noise contribution is the main rationale for applying modulation techniques in high sensitivity spectroscopy. Obviously, this contribution can be evaded in frequency space by applying even higher modulation frequencies. At high enough frequencies, the total system noise is no longer dominated by the $1/f$ noise, and the frequency independent thermal and shot noise contributions determine the SNR [Eq. (1)].

The ultimate detection sensitivity is reached in quantum limited conditions, i.e., when $1/f$ noise can be neglected and shot noise is the dominant noise contribution. According to Eqs. (2) and (3), the quantum limited performance requires a minimum radiation power incident on the detector of

$$P_{\text{min}} = \frac{2kThc}{e^2 \eta \lambda R_{\text{eff}}}, \quad (5)$$

where c is the velocity of light.

III. Experimental Setup

Wideband noise characteristics were investigated in the frequency range from 5 to 500 MHz using a PbEuSn MBE laser made at the Fraunhofer Institute for Metrology.²⁶ The experimental setup is shown in Fig. 1. The laser was mounted in a liquid N_2 cooled Dewar and operated at 1538 cm^{-1} using a current of 563 mA and a temperature of 85 K. The laser current was chosen to be far above the threshold of 200 mA to reduce excess noise due to spontaneous emission and to obtain higher optical output power. The laser power was determined by focusing the laser output by an $f/1.5$ BaF₂ lens on an electronically calibrated pyroelectric detector (Rs-5900, Laser Precision Systems) and it was $521 \mu\text{W}$. Then an infrared neutral density (ND) filter was inserted in the beam and its optical density was measured to be 0.33.

The noise measurements were made by focusing the unattenuated beam on a reverse-biased photovoltaic

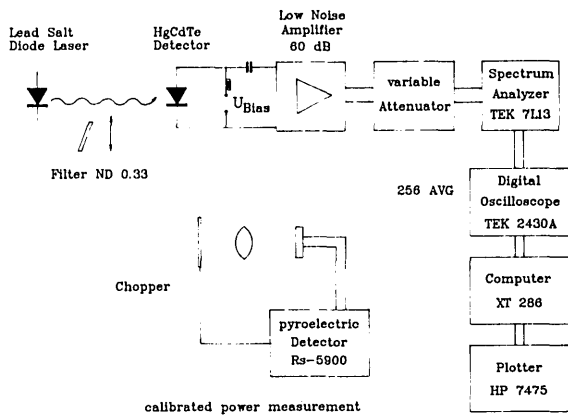


Fig. 1. Experimental setup for the investigation of wideband noise characteristics of lead-salt diode lasers: upper, determination of the noise spectra with and without an attenuator; lower, determination of the laser output power.

mercury cadmium telluride detector (Société Anonyme de Telecommunication) with a quantum efficiency of 76% and a -3 -dB cutoff frequency at 270 MHz. The detector output was amplified by a 60-dB low noise amplifier (Société Anonyme de Telecommunication) with a 5–500-MHz bandwidth and analyzed by a spectrum analyzer (Tektronix 7L13). The internal calibration of the spectrum analyzer was checked by an external precision attenuator (JFW Industries). To achieve a readout accuracy of 0.1 dB, the output of the spectrum analyzer was averaged 256 times by a digital oscilloscope (Tektronix 2430A). The averaged noise spectra were transmitted to a computer for further data processing.

Great care was taken to prevent rf pickup from fm radio stations by suitable shielding and grounding of the whole setup. In the optical path of the setup two off-axis parabolas were used to collimate the laser output and to focus the beam on the detector. Reflective optics were selected to minimize feedback from the surfaces of optical components. But two BaF_2 windows at the laser and detector Dewars could not be avoided. Optical feedback noise appeared when a neutral density filter was inserted in the laser beam. This feedback could be reduced by proper adjustment of the filter.

IV. Results and Discussion

A typical wideband noise spectrum of the lead-salt diode laser shown in Fig. 2 illustrates the different noise contributions. From 5 to ~ 170 MHz the $1/f$ noise rendered the dominating noise contribution. This noise is attributed to intrinsic laser noise and detector excess noise as described in Sec. II. In addition, other pink noise components were observed: feedback noise due to reflections of radiation back in the laser crystal and detector spot noise due to vibration induced movements of the beam focus over the inhomogeneous detector surface. They could be reduced by suitable optical adjustment. Above 170 MHz the shot noise dominated up to ~ 270 MHz, the cutoff frequency of the detector. Above 270 MHz the

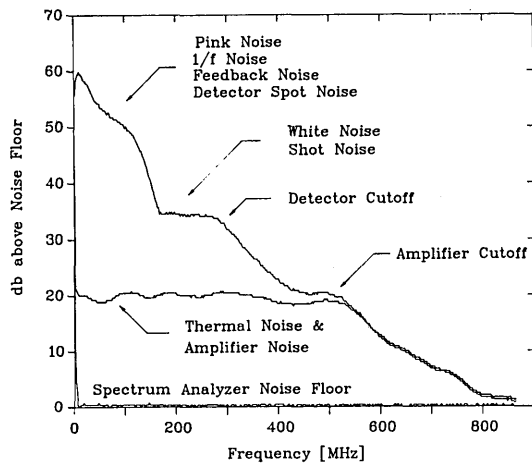


Fig. 2. Typical wideband noise spectrum of a lead-salt diode laser.

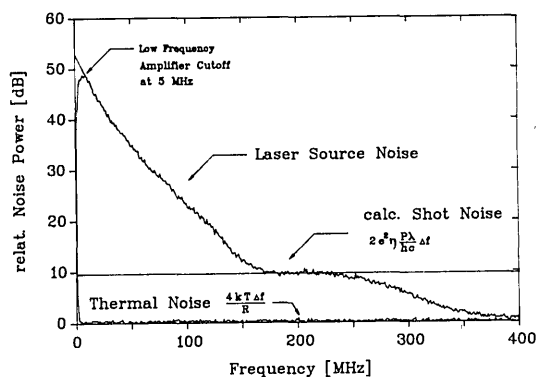


Fig. 3. Lead-salt diode laser noise spectrum measured with a spectrum analyzer with 0.3-MHz bandwidth and averaged over 256 scans. The lower trace shows the thermal noise level of the MCT detector and preamplifier combination determined with the laser switched off. The upper trace shows the noise of the laser without any modulation. The very low frequency part of this trace is linearly extrapolated to dc. The line at 9.3 dB shows the calculated shot noise level above the thermal noise. The potential SNR improvement by moving from low to high frequencies is >40 dB.

noise was attenuated by the detector rolloff and above 500 MHz additionally by the detector preamplifier cutoff. With the laser switched off the thermal noise was not frequency dependent up to the preamplifier cutoff.

A noise spectrum with proper optical alignment is shown in Fig. 3. The frequency dependence of the detector/preamplifier combination thermal noise was recorded with the laser off (no light). Then the laser was turned on (light on) and the steplike spectrum with the pink and the white noise components was acquired. In addition to the frequency cutoff of the detector the spectrum shows the low frequency preamplifier cutoff at 5 MHz. The noise spectrum became white (frequency independent) around 170 MHz at 9.5 dB above thermal noise. This value will now be compared to the calculated relative shot noise level. According to Nyquist's theorem²⁷ only ohmic elements contribute to the Johnson noise current. Thus the

effective amplifier input resistance of 180Ω has to be used instead of the nominal $50\text{-}\Omega$ high frequency impedance. With an effective load resistor temperature of 288 K the shot noise level above the thermal noise was then calculated:

$$\frac{P_{sn} + P_{th}}{P_{th}} = \frac{e^2 \eta \lambda P R_{eff}}{2 k h c T} + 1 = 9.3 \text{ dB.} \quad (6)$$

This result is in excellent agreement with the actually measured value, which was 9.5 dB (Fig. 4), indicating that the dominant noise contribution is indeed the quantum shot noise. Note that the optical power of $521 \mu\text{W}$ used in this experiment by far exceeds the minimum power of $67 \mu\text{W}$ [as calculated from Eq. (5)] necessary to achieve quantum limited performance.

The above conclusion is further corroborated by a series of noise level measurements at attenuated laser power as shown in Fig. 4. Great care was exercised to calibrate the spectrum analyzer with external attenuators and frequency markers. For the noise level measurements a light on noise spectrum was first recorded at full laser power ($521 \mu\text{W}$). Then a neutral density filter was inserted in the laser beam to reduce the incident optical power by 3.3 dB corresponding to the measured optical density of 0.33 . The reduced signal is displayed as the middle trace in Fig. 4. The measured attenuation in the white noise region from 170 to 240 MHz was 3.2 dB , in excellent agreement with the value of 3.3 dB expected for the shot noise dominated regime.²⁸ The authors want to point out that the shot noise limited frequency domain depends on laser and detector parameters. With different laser structures, increasing laser power, higher detector quantum efficiency, different detector bias current, and less contact noise, other quantum limited regions can be found and used for FM spectroscopy.

The measurements of both the noise levels and the laser power dependence clearly demonstrate that the frequency domain above 170 MHz is a shot noise limited regime. Thus an ultimate quantum limited sensitivity in a frequency modulated TDLAS system is expected at frequencies in this domain. In connection with the current discussion of the merits of different frequency modulation schemes,⁹⁻¹¹ we would like to point out that the quantum limitation constitutes a fundamental sensitivity limit. In theory, therefore, the ultimate sensitivity of frequency modulated TDLAS instruments should be the same regardless of the specific FM technique used.

In addition, the noise measurements shown in Fig. 3 demonstrate a considerable noise reduction of more than 40 dB in going from the low frequency region below 1 MHz (used in the present derivative TDLAS systems) to the high frequency region beyond 170 MHz . This noise reduction is smaller than the noise reduction of more than 80 dB reported by Hall *et al.*¹⁴ for a ring dye laser running at $300 \mu\text{W}$ and frequency shift from 10 kHz to the $\sim 1/f$ noise cutoff of 2 MHz . The $1/f$ noise cutoff frequency of our Pb-salt laser diode is much higher, and presumably such a high cutoff could be the reason for the Eng *et al.*²⁰ observa-

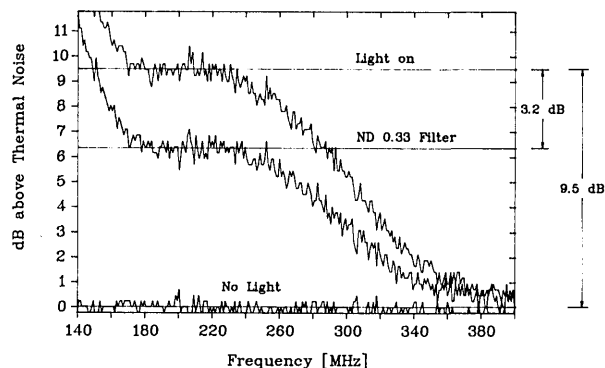


Fig. 4. Noise spectra of the same diode laser at the same operating conditions as in Fig. 3. Additionally, the noise reduction by 0.33 attenuation of the incident laser power is shown indicating the shot noise limited regime above 170 MHz .

tion of an apparently flat noise spectrum for their Pb-salt laser in the $4\text{--}200\text{-kHz}$ frequency range.

The noise reduction of 40 dB when the FM technique is used in the quantum limited frequency domain implies that the detection sensitivity of the present derivative TDLAS systems could theoretically be improved by more than a factor of 100 . In reality, side effects such as etalon formation, pick up of high frequencies, and residual amplitude modulation (RAM) may reduce the potential sensitivity improvement. However, techniques² are available to cope with these problems and by applying them the ultimate sensitivity can probably be approached. Work is in progress in our laboratory to demonstrate the improved performance of a FM TDLAS system directly by measuring atmospheric trace species.

V. Conclusions

The wideband noise characteristics of a PbEuSe laser diode have been measured up to 500 MHz . At frequencies below 170 MHz , $1/f$ type noise dominated and at very low frequencies (5 MHz) it was $\sim 40 \text{ dB}$ above thermal noise. Above 170 MHz on the other hand, the noise was dominated by photon shot noise. This important conclusion was inferred from careful independent measurement of the noise level and of the laser power dependence. With $521 \mu\text{W}$ of incident laser power the shot noise was 9.5 dB above thermal noise and, consequently, by shifting from the very low frequencies to the shot noise limited frequency regime the noise can be reduced by more than 40 dB . These results indicate that the sensitivity of the present TDLAS instruments operated below 1 MHz can be improved by more than a factor of 100 when frequency modulation at frequencies above 170 MHz is used and when etalon effects, RAM, and other possible side effects are effectively suppressed. Such sensitivity improvements open new prospects for the construction of faster and cheaper TDLAS instruments.

The authors would like to thank M. Tacke from the Fraunhofer Institute for Metrology at Freiburg, F.R. Germany, for providing MBE lasers for these measure-

ments. This work has been funded by the German Ministry of Research & Technology (BMFT).

References

1. R. S. Eng, J. F. Butler, and K. J. Linden, "Tunable Diode Laser Spectroscopy: Invited Review," *Opt. Eng.* **19**, 945 (1980).
2. C. R. Webster, R. T. Menzies, and E. D. Hinkley, "Infrared Laser Absorption: Theory and Applications," in *Laser Remote Chemical Analysis*, R. M. Measures, Ed. (Wiley, New York, 1988), p. 163.
3. D. R. Hastie, G. I. Mackay, T. Iguchi, B. A. Ridley, and H. I. Schiff, "Tunable Diode Laser Systems for Measuring Trace Gases in Tropospheric Air," *Environ. Sci. Technol.* **17**, 352A (1983).
4. R. Grisar, H. Preier, G. Schmidtke, and G. Restelli, Eds., *Monitoring of Gaseous Pollutants by Tunable Diode Lasers* (D. Reidel, Dordrecht, Holland, 1987).
5. J. Reid, B. K. Garside, J. Shewchun, M. El-Sherbiny, and E. A. Ballik, "High Sensitivity Point Monitoring of Atmospheric Gases Employing Tunable Diode Lasers," *Appl. Opt.* **17**, 1806 (1978).
6. M. Gehrtz, W. Lenth, A. T. Young, and H. S. Johnston, "High-Frequency-Modulation Spectroscopy with a Lead-Salt Diode Laser," *Opt. Lett.* **11**, 132 (1986).
7. D. E. Cooper and J. P. Watjen, "Two-Tone Optical Heterodyne Spectroscopy with a Tunable Lead-Salt Diode Laser," *Opt. Lett.* **11**, 606 (1986).
8. D. E. Cooper and R. E. Warren, "Two-Tone Optical Heterodyne Spectroscopy with Diode Lasers: Theory of Line Shapes and Experimental Results," *J. Opt. Soc. Am. B* **4**, 470 (1987).
9. D. E. Cooper and R. E. Warren, "Frequency Modulation Spectroscopy with Lead-Salt Diode Lasers: A Comparison of Single-Tone and Two-Tone Techniques," *Appl. Opt.* **26**, 3726 (1987).
10. N.-Y. Chou and G. W. Sachse, "Single-Tone and Two-Tone AM-FM Spectral Calculations for Tunable Diode Laser Absorption Spectroscopy," *Appl. Opt.* **26**, 3584 (1987).
11. L. Wang, H. Riris, C. B. Carlisle, and T. F. Gallagher, "Comparison of Approaches to Modulation Spectroscopy with GaAlAs Semiconductor Lasers: Application to Water Vapor," *Appl. Opt.* **27**, 2071 (1988).
12. G. C. Bjorklund, "Frequency-Modulation Spectroscopy: A New Method for Measuring Weak Absorptions and Dispersions," *Opt. Lett.* **5**, 15 (1980).
13. M. Gehrtz, G. C. Bjorklund, and E. A. Whittaker, "Quantum-Limited Laser Frequency-Modulation Spectroscopy," *J. Opt. Soc. Am. B* **2**, 1510 (1985).
14. J. L. Hall, T. Baer, L. Hallberg, and H. G. Robinson, "Precision Spectroscopy and Laser Frequency Control Using FM Sideband Optical Heterodyne Techniques," in *Laser Spectroscopy V*, A. R. W. McKellar, T. Oka, and B. P. Stoicheff, Eds. (Springer-Verlag, Berlin, 1981), p. 16.
15. N. C. Wong and J. L. Hall, "Servo Control of Amplitude Modulation in FM Spectroscopy: Demonstration of Shot-Noise-Limited Detection," *J. Opt. Soc. Am. B* **2**, 1527 (1985).
16. W. Lenth, "Optical Heterodyne Spectroscopy with Frequency- and Amplitude-Modulated Semiconductor Lasers," *Opt. Lett.* **8**, 575 (1983).
17. W. Lenth, "High Frequency Heterodyne Spectroscopy with Current-Modulated Diode Lasers," *IEEE J. Quantum Electron.* **QE-20**, 1045 (1984).
18. P. Pokrowsky, W. Zapka, F. Chu, and G. C. Bjorklund, "High Frequency Wavelength Modulation Spectroscopy with Diode Lasers," *Opt. Commun.* **44**, 175 (1983).
19. W. Lenth and M. Gehrtz, "Sensitive Detection of NO₂ Using High Frequency Heterodyne Spectroscopy with a GaAlAs Diode Laser," *Appl. Phys. Lett.* **47**, 1263 (1985).
20. R. S. Eng, A. W. Mantz, and T. R. Todd, "Low-Frequency Noise Characteristics of Pb-Salt Semiconductor Lasers," *Appl. Opt.* **18**, 1088 (1979).
21. J. B. Johnson, "Thermal Agitation of Electricity in Conductors," *Phys. Rev.* **32**, 97 (1928).
22. W. Budde, *Physical Detectors of Optical Radiation* (Academic, Orlando, FL, 1983).
23. C. E. Hurwitz, "Detectors for the 1.1 and 1.6 Micrometer Wavelength Region," *Opt. Eng.* **20**, 658 (1981).
24. W. Schottky, "Über spontane Stromschwankungen in verschiedenen Elektrizitätsleitern," *Ann. Phys. (Leipzig)* **57**, 541 (1918).
25. E. L. Dereniak and D. G. Crowe, *Optical Radiation Detectors* (Wiley, New York, 1984).
26. Fraunhofer-Institute for Metrology, Heidenhofstrasse 8, D-7800 Freiburg, F.R. Germany,
27. H. Nyquist, "Thermal Agitation of Electric Charge in Conductors," *Phys. Rev.* **110** (1928).
28. The expected 6-dB noise reduction in the $1/f$ region is not seen due to attenuator induced feedback noise adding to the expected 6-dB reduction.

Of Optics continued from page 1596

John Strong is a past President of the Optical Society of America. Among his many honors are the Longstreth Medal of the Franklin Institute (1939), the Frederic Ives Medal of the Optical Society (1956), and the Gold Medal of the Society of Photo-Optical Instrumentation Engineers (1977). He has published over 150 scientific papers, reports, and book reviews; 14 patents; and a second book, *CONCEPTS OF CLASSICAL OPTICS* (Freeman, 1958). When he decided to update his *PROCEDURES IN EXPERIMENTAL PHYSICS*, he elected to eliminate chapters that had become obsolete and replace some of them with chapters on the history of optics. He thought that the title, "Appreciation of Experimental Physics," was appropriate. One publisher objected to the inclusion of such material, so John persuaded Marcel Dekker to publish the revision in 1988, now named *PROCEDURES IN APPLIED OPTICS*. His best publica-

tion is still to come, an autobiography now being written. A shorter biography was recorded in 1985 in the oral history project of the National Air and Space Museum of the Smithsonian Institution.

John told me that in Chapter 1 of his autobiography he compares the account of the Creation given in Genesis with that described as the Big Bang theory. I asked whether he had seen the concise account of the Big Bang given in a recent issue of *Modern Maturity*, a publication of the American Association of Retired Persons. He said he had seen it and had phoned several of his astronomy colleagues to inquire what the present status of the theory was. One replied, "The Hubble Constant isn't constant any more." Another said, "Even space is expanding." John decided to hold fast to the classic Big Bang with the remark that, "Anything that is good enough for the AARP is good enough for me!"