Anthony E. Siegman

1931–2011

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by Stephen E. Harris

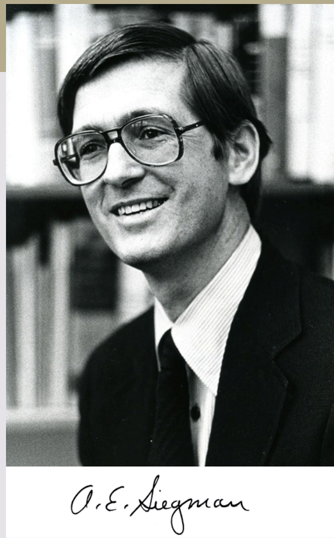
NATIONAL ACADEMY OF SCIENCES

ANTHONY E. **SIEGMAN**

November 12, 1931–October 7, 2011

Elected to the NAS, 1988

Professor Anthony E. Siegman (Tony), a renowned laser physicist, inventor, and educator died on October 7, 2011, a few weeks short of his 80th birthday. Siegman is known for his contributions to laser resonators and optical beam propagation, for his co-authorship of the first paper that theoretically predicted what would later be called parametric fluorescence, and for primary contributions to laser mode-locking. He was an educator of the first order, especially well known for his widely used textbook *Lasers,* for his many productive and talented students, and for his overall impact on optical science.



By Stephen E. Harris

I first met Tony Siegman in his office at Stanford on a hot September afternoon in 1960. After graduating from RPI in 1959 I had been a member of the Technical Staff at Bell Telephone Laboratories (BTL) in the group of Dirac Scovil, Joe Geusic, Erich Schulz-DuBois and Bob Degrasse. This group was developing ultra-low noise masers that would, within a few years, be used for observation of the microwave background radiation that as a remnant of the big bang pervades the universe. At BTL I had finished a paper describing the design of a slow wave structure for a microwave rutile amplifier (maser) and I asked Tony if I could continue, under his direction, toward a PhD. At that time Tony had three students working on microwave masers and was also working on what was to become his classic textbook *Microwave Masers*. A few months earlier, in May 1960, Theodore Maiman at Hughes Research Laboratory had demonstrated the first ruby laser. In September 1960 Tony Siegman had taken on Burton McMurtry as his first PhD student to work on lasers. (Years later, Burton would become an esteemed venture capitalist and Chairman of the Board of Trustees of Stanford University.) Tony asked me to consider working on lasers instead of masers. In January 1961, I joined Tony's research group as his second laser student.

The early years (from OSA Oral History, May 5, 2008)

Tony Siegman was born in Detroit in 1931 and brought up in rural Michigan. His mother was an elementary school teacher and his father was the controller for an ice and fuel company. Tony did well in school, and was especially interested in making things work. In his 2008 Optical Society of America (OSA) oral history, Tony states:

> *And I don't know that I had a large interest in science or any early 'a ha' moment about science at that time. In fact, I think in comparison to what I've seen in some of these oral histories from others where people are making deliberate choices as they go along, my feeling looking back on my life is that I've been very, very fortunate, and a lot of lucky things have happened to me, mostly through other people somehow identifying my talents or something and pointing me in the right direction. And maybe the first of those lucky events, and what eventually at least led into my career in optics was the fact that sometime in the late 1940's, Harvard College decided that it wanted to institute a new program called the National Scholars Program. And somehow, through miracles that I've no conception of actually, I won one of the two from Michigan.*

In the autumn of 1949 Tony started at Harvard. Describing his early years at Harvard and continuing in his modest manner, he notes:

> *And sometime in the second year, I realized that going at this rate, at the end of three years, I would be just two courses short of graduating. And so I guess partly as a matter of economy and just because it looked like an easy thing to do, I stayed in Cambridge for the summer between what would've been sophomore and junior years and took two extra courses, and graduated at the end of the third year. And, again much to my surprise at the time as I hadn't even been thinking about this, I learned I had graduated summa cum laude in three years flat.*

In the summer of 1952, having obtained his A.B. degree from Harvard, Siegman joined the Hughes Research Laboratory cooperative plan where he would do research on traveling wave tubes, and at the same time, work toward an MS degree in applied physics at UCLA.

Tony Siegman (about 1960).

Traveling wave tubes at Hughes Research Laboratory

Following the critical success of radar during the Battle of Britain in the Second World War, there were fast-moving efforts to develop microwave technology and apply that technology to the next generation of radar systems. Essential ingredients for the development of this microwave technology were low-noise broadband amplifiers. At two centers of research in the United States, the MIT Radiation Laboratory and Hughes Research Laboratory, scientists were striving to attain lower noise and larger bandwidth amplifiers. In terms of bandwidth the traveling wave tube (TWT) was the clear leader. In terms of low noise the microwave maser and the parametric amplifier were the leading contenders.

Many of the concepts associated with traveling wave tubes were destined to play a major role in laser science. These include seemly obvious concepts like gain, and oscillation, and less obvious concepts such as phase and group velocity, slow wave structures, coupled modes, and even phase conjugation (Chap Cutler). Tony Siegman's first publication (1953) is entitled "Helix Impedance Measurements Using an Electron Beam." The helix is a prototype example of a slow wave structure. Though its group and phase velocity are easily calculated, its impedance, which in turn determines both the gain and output power of the traveling wave tube were more difficult to calculate and required experimental verification.

In 1954 Siegman obtained his MS degree in applied physics, and Stanford Professor Dean Watkins asked him if he would like to study, under his direction, toward a PhD. Tony moved to Stanford and began his PhD work on low noise traveling wave tubes.

In 1957 Siegman and Watkins published two papers that developed a new technique for the analysis of traveling wave tubes. These are entitled "Multivelocity Electron Beams by the Density-Function Method", and "Density-Function Calculations of Noise Propagation on an Accelerated Multivelocity Electron Beam." The density function method is a formalism that makes use of the electron density as described in phase space. By combining the phase-space-conserving Liouville theorem and the appropriate force equations, one obtains partial differential equations for the dc and ac components of the electron beam. These papers are a first example of Siegman's ability to blend sophisticated mathematics with strong physical insight. This work was sufficiently strong that in 1956 Tony was offered and accepted an assistant professorship in electrical engineering at Stanford.

Microwave Masers

Some background: In 1951, after working on radar during World War II, Charles Townes proposed the ammonia maser. In 1953 Jim Gordon and Townes demonstrated this new source of electromagnetic radiation and thereby blended classical electromagnetic theory with quantum mechanics and atomic physics. In 1956 Nico Bloembergen in a classic *Physical Review* paper described how one could pump a three level solid state system so as to make a new type of maser amplifier.

In December of 1958 Arthur Schawlow and Charles Townes published their classic paper "Infrared and Optical Masers." In the middle of 1959 Charles Townes chaired the historic symposium at Shawanga Lodge in the Catskill Mountains. At his invitation, Tony Siegman helped to organize the program. In May of 1960 Theodore Maiman at Hughes Research Laboratories, and previously a student of Willis Lamb at Stanford, experimentally realized the first laser.

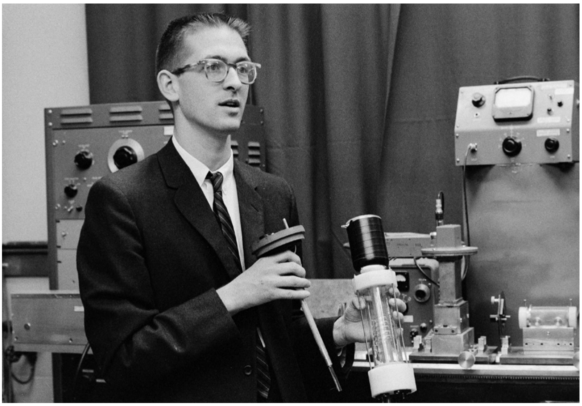

Tony at that now famous meeting.

During his career Tony would make two major changes in the direction of his research. The first occurred in 1957 as he began his assistant professorship at Stanford and had the foresight to hire three students to work on microwave masers. With these dissertations still in progress, and his textbook, *Microwave Masers*, not quite finished, in 1960 Siegman made his second major change and began work with Burton McMurtry as his first laser student.

Longitudinal modes of the ruby laser

Burt had obtained his BA and BS in electrical engineering from Rice University and was doing research on traveling wave tubes at GTE's Sylvania Electronic Systems division in Mountain View, California. Tony suggested that they use a traveling wave tube to observe the mixing of the axial modes of a ruby laser. Following a design from Raytheon, Burt constructed an early laser with a rod length of 14 cm and an axial mode spacing of about 600 MHz. Though, initially, it was Tony's intent to construct a TWT with a photo-cathode, Burt suggested that because of the high power of the ruby laser that it might be possible to avoid the construction of a new tube and use an ordinary thermionic cathode. This surmise was correct and Siegman and McMurtry observed the beats between the third and seventh nearest neighboring modes. This observation was the first to show that different axial modes may oscillate simultaneously. In the conclusion of their paper the authors note that their TWT could be viewed as a super-heterodyne receiver with the cathode acting as the mixer and the helix as an amplifier.

Music on a beam of laser light



Tony with apparatus for sending music on a beam of light. The modulator with the wave-guide on top operated at 3 GHz, and the optical table was a lathe bench. Tony is holding an early Ruby laser with a helical flashlamp.

I (Steve Harris) came to Stanford in autumn 1960 and in early 1961 joined Tony Siegman's group as a Ph.D. student. My first task was to construct a microwave S-band (3 GHz) microwave modulator. I did this by following Ivan Kaminow's KDP cavity design and using an available magnetron with a power of about a megawatt. The experiment worked immediately and Tony, Burt and myself realized that we were in a position to transmit a microwave signal on a beam of deep red light from the laser that Burt McMurtry had constructed. (Previously Ivan Kaminow had demonstrated an X-band KDP modulator, but since he did not have a fast detector, he accomplished the observation by observing the change in the dc transmission as the microwave driving pulse was applied.) I remember our excitement on seeing the envelope of a microwave pulse appear on the scope at the other end of a lathe that served as our optical bench.

Tony then suggested that I work on the problem of detecting frequency modulated light. To do this, I suggested the use of a birefringent crystal of Calcite as an early FM to AM discriminator. Progress was rapid and in early 1963 we borrowed a 6328 angstrom He-Ne laser from Bob Rempel at Spectra Physics. Before long we were sending music, sub-carrier, on an X-band frequency modulated beam of red light

Quantum Fluctuations and Noise in Parametric Processes

Beginning in 1961 Tony was working on what was to be his most fundamental contribution to quantum optics. The key paper is entitled "Quantum Fluctuations and Noise in Parametric Processes." The paper was co-authored by Bill Louisell and Amnon Yariv (at that time both at Bell Telephone Laboratories).

In 1961 workers throughout the world were seeking low noise amplifiers. The maser had been invented and was viewed as a strong competitor to the varactor based parametric amplifier. The noise properties as a function of the non-zero temperature of the parametric amplifier were known, but there was no prediction or understanding of the noise properties as the temperature approached absolute zero. The authors, by quantizing the optical field and working in the Heisenberg representation, predicted that even at zero temperature that the oscillator would emit noise photons in proportion to the gain of the amplifier, and that the amplifier would have the same noise properties as that of an ideal maser. Though recognized as primary, it would take some years for this paper to become a classic.

The key step that would follow was the elucidation and wide acceptance of Bell's inequalities, and the recognition by Leonard Mandel and colleagues that an optical parametric oscillator produces pairs of entangled photons with properties that, even now, are viewed as amazing. As an example, if a monochromatic pump with angular frequency ω_p is used to generate photons termed as the signal and idler frequencies, then if an observer measures the frequency of the signal photon ω_s at location A, then an observer at a location B must necessarily measure an energy conserving idler frequency $\omega_i = \omega_p - \omega_s$. But instead, if the observer at A measures the time of arrival of the signal photon, then an observer at B will know the time that the idler photon will arrive, but will have no knowledge of its frequency. The measurements, as described above, are not limited by the time-frequency uncertainty principal, i.e. both frequency and time of arrival may, in principal, be measured to arbitrary accuracy. Quantum mechanics allows non-classical correlations that remain strange and interesting. The field of quantum optics, is often traced to the paper by Weinberg and colleagues who first measured the time of arrival of signal and idler photons. In turn, the Weinberg paper traces the opening of this field to the paper of Louisell, Siegman, and Yariv.

As a further example of the impact of this paper: One of the most exciting physics events of recent years is the recent observation of gravitational waves by the LIGO observatories. To observe the strain associated with a gravitational wave requires the ability to measure a length change on scale of 10^{-18} meters. A fundamental limit on this measurement results from the statistical fluctuations in the arrival time of the photons at the interferometer output. If one is interested in measuring phase and if one replaces the fluctuations of the coherent laser state with those of a squeezed vacuum state then significant improvements in sensitivity may be obtained. It turns out that this squeezed vacuum state is the output "noise" of the Siegman and colleagues 1961 paper.

The unstable resonator

One of Tony Siegman's foremost contributions is his invention of the unstable optical resonator, a conceptual advance that made high-power lasers with high beam quality possible. This widely used configuration is the resonator of choice for lasers for which the lasing volume is large and the resonator length is small (i.e., in which the Fresnel number is larger than unity). In these systems, the unstable resonator allows a high quality, near diffraction limited output laser beam combined with efficient energy extraction from the laser medium. In a stable resonator, the mirror configuration corresponds to a stable periodic focusing system, and the lasing region has a long and slender profile. Conversely, an unstable resonator corresponds to a divergent periodic focusing system. On repeated bounces, the beam expands to fill the entire cross section of the lasing media. This technique allows excellent beam characteristics and discrimination against higher-order transverse modes.

In early 1961, when Tony began working on the unstable resonator, Burt McMurtry had built a rod-shaped ruby laser surrounded by a helical flash lamp, which was in turn fired by a large capacitor bank. The ends of the ruby rod were flat, and to make a resonator one evaporated a thin aluminum coating onto the ends of the rod. After the laser was fired a few times the aluminum at the edges of the circular end face burned away and the laser energy emerged as a narrow ring with a diameter of the lasing ruby rod. The questions raised by this system were: Is this really a resonator, i.e. the light did not appear to retrace its path? If it is a resonator, how should one choose its length, diameter, and output coupling so as to maximize its output power? One could instead curve the ends of the rod so as to make a stable resonator. But by doing so they would lose the energy that is stored in much of the rod. As is often the case in science, an accidental discovery, that is the burning of the aluminum coating and optical leakage around the rim led to Tony's invention of the unstable resonator. Uses of the unstable resonator have continued to increase through the years with broad application to both medical devices and industrial processing.

Optical heterodyning

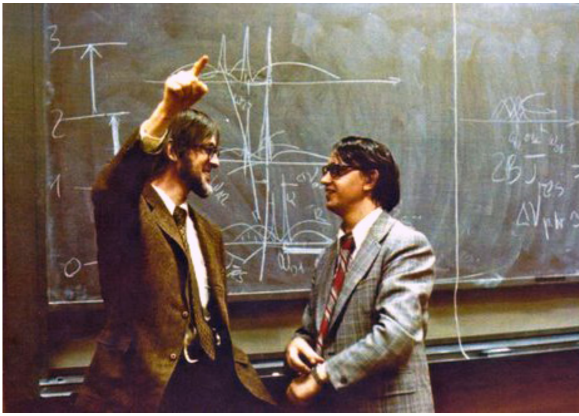
As I write this in 2017, optical heterodyning is playing an ever more important role in optical communications. Siegman addressed optical heterodyning 50 years ago in his paper "The Antenna Properties of Optical Heterodyne Receivers." The essential point of this paper is that a heterodyne receiver is, in essence, an antenna. Therefore the product of the capture area of an optical receiver times its angular field of view is approximately equal to the square of the wavelength, together with the corollary: When optical heterodyning is used to measure a scattering process, for example Doppler scattering, that the ratio of measured scattered light to incident light may not exceed the density of scattering atoms times the single particle scattering cross section times $\lambda^2/4\pi$.

The applicability of a laser pulse to send information over a long distance, or instead to sense a small change in length depends not only on the power of the laser, but also on the noise that is inherent to the laser pulse. When working at microwave frequencies the noise per mode is the product of the Boltzman constant and the temperature. At optical frequencies it is the product of the Planck constant and the optical frequency. At microwave frequencies where resonators are generally closed the term "mode" is well defined and accurate predictions of the noise of laser amplifiers are possible. At optical frequencies the approximation of a closed mode, most often, is correct for stable optical resonators. But for some resonators and in particular for the unstable resonator this is not the case and the output of a laser beam may have either higher (excess) noise, or less noise, than expected. In a classic 1989 paper entitled "Excess Spontaneous Emission in Non-Hermitian Optical Systems. I. Laser Amplifiers" Siegman recognized the essence of the problem: All open resonators have at least some loss, and the modes of such resonators are not self-adjoint. They are therefore not power orthogonal and expansion into these modes requires the use of a bi-orthogonal basis set. Of practical importance, in laser amplifiers, but not in free running laser oscillators, this excess noise may be balanced out and the usual quantum noise limit recovered. As in so much of Siegman's work, this paper shows his special blend of physical insight and mathematical ability.

Contributions to mode locking

One of Siegman's most important papers was written in 1970 and co-authored with his student Dirk Kuizenga. The paper "FM and AM Mode Locking of the Homogeneous Laser-Part I" introduced both a new method of analysis and a new paradigm for understanding mode locked lasers.

Early mode locked lasers make use of either an AM or an FM modulator inside the laser cavity. The frequency of the modulator is tuned to, or near, the cold cavity longitudinal inter-mode spacing. First experiments demonstrating AM mode locking were performed at Bell Telephone Laboratories in early 1964 by Hargrove, Fork, and Pollack. These workers made use of an acousto-optic modulator to produce a comb of frequencies whose Fourier transform is a train of temporally narrow pulses with a repetition frequency is equal to that of the modulation frequency. First experiments on FM mode locking were performed by Russell Targ and myself later in 1964, and made use of an inter-cavity KDP phase modulator driven near to, but not exactly at the cavity mode spacing frequency. The result was a comb of sidebands with approximately Bessel Function amplitudes. The theory of mode locked lasers was underway in the year or so preceding the experimental work with papers by E.I. Gordon (1963), A. Yariv (1964), M. DiDomenico (1964), and S. E. Harris and O. P. McDuff (1964). Of importance these theoretical papers were all based on coupled mode theory as applied in the frequency domain. Though the predictions of these papers were correct and agreed with experiment, the frequency domain approach was inherently complicated.



Tony Siegman with Vladelen Letokov (about 1974).

The 1970 approach of Siegman and Kuizenga was very different. The authors worked completely in the time domain, assumed that there was a short pulse in the cavity, and followed this pulse once around the cavity with the requirement that the pulse does not change shape or phase. (This is similar to an approach used by Cutler when studying travelling wave microwave regenerative amplifiers.) This approach yields analytical expressions for the pulse length, pulse bandwidth, and frequency chirp of the mode locked pulse.

Tony Siegman at OSA's LaserFest (2010). (Photo courtesy of the Optical Society.)

When the modulator is detuned, further results include the prediction of the shift of the pulse spectrum off of line center, and for the FM case, prediction of an inherent frequency chirp.

Branching off from his work on frequency modulation, in 1976 Tony Siegman suggested the use of a tunable laser induced grating for the study of excited atomic and molecular states. Here two cw lasers with a variable frequency difference are used to create a time varying excited state grating. Another cw laser is diffracted off of this moving grating to yield the impulse response of the excited state. This expanding field was reviewed in 1986 by Trebino, Barker and Siegman.

Mode locked lasers continue to play a critical role in optics and metrology. With the introduction of Kerr Lens mode-locking, and the interplay of the nonlinear index and the properties of photonic band gap fibers, it is now possible to obtain frequency combs that span many octaves. This has resulted in extraordinary advances in metrology, in particular the work of John Hall and Theodore Hansch for which they and Roy Glauber shared the 2005 Nobel Prize in Physics. The techniques and concepts that are developed in the Kuizenga-Siegman paper have played a major role.

Tony with Lillie and Barnaby at Lake Tahoe.

Laser beam quality, gain guiding, and index anti-guiding

Siegman is known for his many contributions to techniques for both studying and achieving optimized laser beam propagation. In particular his “M square” technique has become the industrial standard for measurement and characterization of laser beam quality. This technique is based on his realization that any laser beam may be characterized by a single beam parameter that is a measure of the beam diameter times divergence product; i.e. of the far-field spread of the beam as compared to an ideal Gaussian beam with the same beam waist. Only for a TEM zero-zero gaussian beam will the factor M have the limiting value of unity. This allows the quality of any laser beam to be specified by a single and universally understood number.

High power fiber lasers have increasing applications in optical processing of materials. Siegman’s 2003 paper “Propagating Modes in Gain-Guided Optical Fibers” and his 2007 paper “Gain-Guided, Index-Antiguided Fiber Lasers ” present comprehensive studies of both gain guiding and refractive index anti-guiding. Optical fibers with large diameter typically have a negative index step going from the cladding to the core and would be expected to be anti-guiding. These papers show that gain-guiding allows a stable and confined waveguide mode even in systems characterized by strong index anti-guiding, that is, even in systems whose transverse index profiles will not by themselves support a confined guided mode. Thus allows single mode operation in fibers that have very large (400 microns and larger) core diameters, and therefore, much larger power handling capability than do ordinary fibers.

Contributions to education and leadership

Tony Siegman’s three textbooks *Microwave Solid State Masers* (1964), *An Introduction to Lasers and Masers* (1971), and *Lasers* (1986) have, over time, become standard and often cited references in the quantum optics literature. Because Tony trained as an engineer and had to learn quantum mechanics on his own the approaches in these textbooks provide a somewhat gentle and yet rigorous introduction to what is now a complex literature. By interfacing with quantum mechanics, and in parallel with the vast transition underway at that time from vacuum tubes to transistors, Tony contributed to a new definition of electrical engineering. Amplification was now possible using the quantum mechanical properties of atoms and molecules instead of the kinetic properties of electrons. I quote Burton McMurty: “One of the best descriptions for Tony is that he was a terrific clarifier. He wasn’t a simplifier. Almost nothing that interested him was simple, but he could make complex issues pretty clear and did so in his legendary book, *Lasers.*”

To honor Tony Siegman's contributions to optics, working through the OSA Foundation and with primary donations from Burton and Deedee McMurtry and IPG Photonics, the Optical Society has established the Siegman International School on Lasers. Each summer, this School invites up to 100 graduate students for a week-long program. Students are provided with travel and tuition grants. The first school, with graduate students from throughout the world was held at Stanford in August of 2014. The following Schools were held in Amberg, Germany in 2015, in Barcelona, Spain in 2016, and in Leon, Mexico in 2017.

Tony Siegman served on the OSA Board of Directors in 1976 and again from 1997 through 2000. He was OSA President in 1999 and, in this position, he led important strategic discussions on OSA's role in serving both academia and industry. He encouraged OSA to expand its coverage of laser and optics applications in OSA publications and scientific meetings. He played a key role in creating a culture of philanthropy at OSA by successfully securing donations to endow the Charles Hard Townes Award and setting the stage for the creation of the OSA Foundation. He served on the OSA Foundation Board of Directors from 2003 through 2008. In 2010 he was co-Chair of LaserFest, a major global celebration of the 50th anniversary of the laser.

Family and interests

Tony was an outdoorsman. For many years, he and his wife Jeannie would spend the winters in their cabin near Lake Tahoe where with their two furry snow dogs Lillie and Barnaby, they would cross-country ski and hike. In earlier years Tony and I backpacked and camped in the Sierra with our children. On one occasion, camping in Yosemite National Park, my six year old daughter managed to find her way to a high nearby rock. As I was beginning a call to the park ranger, Tony scaled the rock, and with one arm around my daughter, carried her down. On another occasion he and I were skiing at Sugar Bowl in the Sierra. As the last run of the day approached Tony casually told me that he would spend the night at a cabin about halfway to Squaw Valley. And on downhill skis, and in deep snow, off he went. Tony Siegman is survived by his wife Jeannie Siegman, and his children Winn, Patrick, and Elaine.

ACKNOWLEDGEMENT

Text and photos in this memoir are drawn from the OSA Oral History Project (conducted on May 5, 2008) by Lee Sullivan (transcript provided courtesy of OSA); from "Tony Siegman's Legacy of Laser Education" by Patricia Daukantas, Optics & Photonics News, July-August 2014, pp. 26-33 (OSA Publishing); as well as from The Optical Society archives, Stanford University archives, the Siegman family archives, and the author's own recollections.

HONORS AND AWARDS

1972 W. R. G. Baker Prize, IEEE

1973 National Academy of Engineering

1977 J.J. Ebers Award, Optical Society of America

1980 R.W. Wood Prize, Optical Society of America

1984 American Academy of Arts and Sciences

1986 Burton J. and Ann M. McMurtry Professor in the School of Engineering at Stanford

1987 Frederic Ives Medal/Jarus Quinn Endowment, Optical Society of America

1988 National Academy of Sciences

2009 Esther Hoffman Beller Medal, Optical Society of America

SELECTED BIBLIOGRAPHY

1953 With D. A. Watkins. Helix impedance measurements using an electron beam. *Journal of Applied Physics* 24:917-922.

1957 Analysis of Multivelocity Electron Beams by the Density-Function Method. *Journal of Applied Physics* 28:1132-1138.

With D. A. Watkins and Hsung-Cheng Hsieh. Density-Function Calculations of Noise Propagation on an Accelerated Multivelocity Electron Beam. *Journal of Applied Physics* 28:1138-1148.

1961 With W. H. Louisell and Amnon Yariv. Quantum fluctuations and noise in parametric processes. 1. *Physical Review* 124:1646-1654.

1962 With B. J. McMurtry. Photomixing experiments with a ruby optical maser and a traveling-wave microwave phototube. *Applied Optics* 1:133-135.

With S. E. Harris and B. J. McMurtry. Modulation and direct demodulation of coherent and incoherent light at a microwave frequency. *Applied Physics Letters* 1:37-39.

1965 Unstable optical resonators for laser applications. *Proceedings of the Institute of Electrical and Electronics Engineers* 53:277.

1966 The Antenna Properties of Optical Heterodyne Receivers. *Proceedings of the IEEE*. 54:1350-1356.

1970 With Dirk J. Kuizenga. FM and AM Mode Locking of the Homogeneous Laser-Part I. *IEEE Journal of Quantum Electronics*. QE-6: 694-708.

1976 Proposed picosecond excited-state measurement method using a tunable-laser-induced grating. *Appl. Phys. Lett*. 30: 21-23.

1978 With J. R. Salcedo, D. D. Dlott. Dynamics of energy-transport in molecular-crystals-picosecond grating transient method. *Phys. Rev. Lett*. 41:131-134.

1986 With Rick Trebino and Charles E. Barker. Tunable-Laser-Induced Gratings for the Measurement of Ultrafast Phenomena. *IEEE Journal of Quantum Electronics*. QE-22:1413-1439.

1989 Excess spontaneous emission in non-Hermitian optical systems. I. Laser amplifiers. *Physical Review A* 39:1253-1263.

Excess spontaneous emission in non-Hermitian optical systems. II. Laser oscillators. *Physical Review A.* 39:1264-1268.

1990 New developments in laser resonators. *Proc. SPIE* 1224:2-14.

1996 With Y. J. Cheng and C. G. Fanning. Experimental Observation of a large excess quantum noise factor in the linewidth of a laser oscillator having nonorthogonal modes *Phys. Rev. Lett.* 77:627-630.

2003 Propagating modes in gain-guided optical fibers. *J. Opt. Soc. Am. A*. 20:1617-1627.

2007 Gain-guided, index-antiguided fiber lasers. *J. Opt. Soc. Am*. *B-Optical Physics* 24:1677-1682.