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Microwave Pioneers: Kam Lau, "μWaves Meet Photons"

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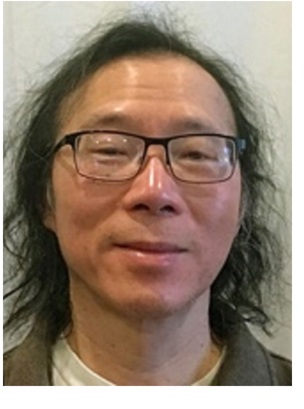
ABSTRACT This article is part of a continuing series of biographical pieces on persons who have made significant and continuous contributions to microwave science, technology, and applications over the course of their careers. It is intended to bring to the reader, especially those new to the field, a portrait of an individual who serves as a role model for the community and a detailed description of their accomplishments. At the same time, it tries to bridge with commonality, the experiences of the subject with those of the scientists, engineers and technologists who are following in their footsteps or hope to establish a similar record of success. The articles are composed only after an extensive face-to-face interview with the subject and are helped immensely by additional input and editing by the subjects themselves. The focus of this article is Professor Kam-Yin Lau, who developed the first photonic source capable of high-fidelity optical modulation at 10 GHz and beyond, and successfully introduced photonics into the traditional microwave disciplines. His work during the 1980s enabled hitherto unattainable long-distant (~50 km) guided transport of microwave signals over optical fibers. These accomplishments helped spur the microwave photonics industry that has transformed both wired and wireless communications networks, and as you will read, several other applications of national and scientific significance. It is appropriate that Professor Lau is the recipient of this year's Microwave Theory and Techniques Society's Microwave Pioneer award for his development and commercialization of RoF (RF-over-Fiber) which launched the microwave photonics industry. As both an industry pioneer and an academic, Professor Lau's accomplishments fit well within the scope of this series. I hope you will both enjoy and learn from his account of where he came from, what motivated his career choices, and the many notable people he interacted with.

INDEX TERMS Microwave photonics, laser diode modulation, hybrid fiber-coax networks, RoF, communications .

Kam-Yin Lau,[1] the only child of working-class parents who migrated from war ravaged mainland China to Hong Kong in the 1940s, was not thinking about science or engineering while a young teenager in the early 1970s. Instead, at age 16, he was consumed by a passion to create modern Chinese ink paintings and was preparing for participation in a prestigious event intended primarily for professional artists - the 1972 Hong Kong Contemporary Art Exhibition. After the show, one of his paintings (Fig. 1) was



[1]This article was compiled after a series of three interviews with Professor Lau on Dec. 1, 2 and 4, 2020. Normally, the interviews would have been face-to-face, but Covid 19 restrictions forced their conversion into video conference sessions. The author was made aware of Professor Lau's long-standing contributions to microwave techniques through MTT Past President and Awards committee chair, Dr. Ed Rezek, on his (Professor Lau's) selection for the MTT Society's 2021 Microwave Pioneer award "for pioneering developments and commercialization of RF over fiber devices, systems and applications which launched the microwave photonics industry." Professor Lau also received the 2013 Pioneer Award from the IEEE Aerospace and Electronics Systems Society (AESS): http://ieee-aess.org/professor-kam-lau-2013-pioneer-award-winner. After reading through his detailed biography and spending 8 interesting hours talking with Professor Lau about his career and his professional experiences and associations, I believe you will concur that there is a lot to be learned from his approach, his enthusiasm, and his varied choices. I hope you will enjoy his story as much as I did. Note that some of the details that appear in this article were taken from an autobiographical account originally prepared by Professor Lau, but not yet published. The author is grateful for this material and the figure which was drawn from that manuscript.

acquired by the Hong Kong Museum of Art for its permanent collection.[2]

Though not considered academically exceptional, Lau did perform reasonably well in science and math in high school. At age 17, while in his senior year, he stumbled on a biography of famed Chinese rocket scientist, Hsue-Shen Tsien[3] in a local bookstore. Tsien was notable not only as the father of Chinese rocketry (he was a graduate student of Theodore von Karman, an aeronautics professor at Caltech during the 1930s known as the father of supersonic flight) but was also considered a co-founder of the Caltech/NASA Jet Propulsion Laboratory (JPL) together with von Karman and other colleagues, and he participated in the early development of aeronautics and rocketry in the US. Lau related that reading Tsien's biography changed his life. His academic focus shifted from art to engineering, and his new goal was to go to Caltech and follow in the footsteps of Tsien. After successful interviews on behalf of the Caltech admissions office with two Caltech alumni then teaching at the Chinese University of Hong Kong, Lau was admitted to Caltech in 1975 with full financial support.

FIGURE 1. Painting #AC1972.020 by Kam-Yin Lau, Hong Kong Museum of Art, acquired 1972.

Lau's first memory of the Caltech campus in sunny Pasadena, California, was the overwhelming odor of marijuana (*to be fair, it was the mid-70s!*) but his training there was definitely not a sojourn into euphoria. Even with his extra year of secondary school coursework in Hong Kong – Form 7 (equivalent to one year beyond grade 12 in in the US system), it is remarkable that he completed both his bachelor's and master's degrees in only 3 years. The feat is even more noteworthy as Lau was a work-study student and maintained several lab assistant, as well as more mundane service jobs, throughout his undergraduate training. Although he did not get as close to walking in Tsien's shoes in pursuing aeronautics as he originally envisioned, he did take a thermodynamics class from Prof. Hans Wolfgang Liepmann, a contemporary of Tsien studying under von Karman. And of course, he had plenty of time to bask in the shadows of the Caltech Guggenheim Aeronautical Laboratory where von Karman acted as the first director, and where Tsien had his lab.

As a foreign national studying under an F1 visa, practical considerations eventually came to bear, and Lau decided that a career in aeronautics was simply not viable for him, either in the US or in China (there wasn't an aerospace program in China at the time). He got interested in electrical engineering instead, and through Professor Hardy Martel, the same Caltech professor that helped steer Carver Mead, another subject of these Pioneer articles [3] into EE, he was introduced to recently arrived professor, John Pierce.[4] Pierce had his undergraduate and graduate education at Caltech in the 1930s, and after an amazing career, had just come back to the university upon his retirement from Bell Laboratories in northern New Jersey. He took Lau under his wing, and when Lau, while browsing through journals in the electrical engineering library, happened upon the then new field of fiber optic communications enabled by another one of Hong Kong's emigres, Charles Kao,[5] he asked Pierce if he might be able to help arrange a summer research opportunity at Bell working on this emergent technology. Pierce picked up the phone on the spot, and placed Kam with Stuart Miller,[6] who was then director of the Optical Communications Research Laboratory at Bell's Crawford Hill facility, down the road from the famous Holmdel complex where Karl Jansky first observed radio waves from the Milky Way in 1931[10].

Kam was in awe of both the historic impact, and the current technical staff at Bell when he arrived in Holmdel, N.J. in the summer of 1977. Residing in a dorm at nearby Monmouth College, he was bussed back and forth to Holmdel each day

[2]Three other paintings by Lau are currently in the collection of the Hong Kong Museum of Education. Photos of these and other works are posted on his U.C. Berkeley web site: https://people.eecs.berkeley.edu/~klau/artwork.html

[3]Hsue-Shen Tsien (also Xuesen Qian) was a fascinating character who was instrumental in establishing early rocketry capability in the US, but who ultimately was caught up in the McCarthy era communist purges and ended up under house arrest (while a Professor at Caltech) until he was deported to China in 1955 in exchange for US pilots captured during the Korean War. After returning to China as a hero, he accomplished just the opposite of what the McCarthy witch-hunt was trying to prevent – helping communist China set up its defense and aerospace program. The referenced biography of Tsien, *Thread of the Silkworm* [1] is a worthwhile read. Tsien came to the US to attend a master's program at MIT in 1935. He later earned a PhD under Theodore von Karman at Caltech, and subsequently became a professor at Caltech. He was a co-author of the first proposal to create and name the Caltech (now NASA) "Jet Propulsion Laboratory" and is considered a co-founder of the facility [2]. With an equivalent rank of a major in the U.S. Air Force, he and von Karman were members of a team that visited Germany and interrogated Werner von Braun at the end of WWII. He died in China in 2009 at the age of 98.

[4]John R. Pierce [4] (Pierce electron gun [5]) had just retired from Bell Laboratories after a stellar career in microwave vacuum techniques and applications. He is also credited for coining the name "transistor" [6]. Pierce came to Caltech as a professor in 1971 and was also the Chief Engineer at the Jet Propulsion Laboratory, which fielded the receiver for the first transcontinental test of *Echo*, Pierce's pioneering stratospheric balloon communications satellite experiment in August 1960 [7].

[5]Sir Charles Kuen Kao [8], 2009 Nobel Laureate in Physics and "father of fiber optics communications" who like Tsien, was a Chinese national who made good as an ex-patriot. Kao came to Hong Kong with his family from Taiwan in 1948, left for UK after high school and returned to China in later life (although not under any detrimental circumstances). He served as vice-chancellor of the Chinese University of Hong Kong (CUHK) from 1985 to 1996. In the early 1980s, while Kao was still an Executive Scientist at ITT, Connecticut he spent significant time visiting with Amnon Yariv's optoelectronics group at Caltech (where Lau would end up). By this time, Lau had already graduated and was working at Ortel, but he visited Caltech often to collaborate with Yariv's students, and got to know Kao personally. Later, whenever Lau visited Hong Kong, he would pay Kao a visit at CUHK, where Kao would treat him to a traditional English afternoon tea. In early 2007, Lau invited Kao to an art exhibition in Hong Kong where one of Lau's Chinese ink paintings was on display. Kao passed away in September 2018.

[6]Stuart E. Miller was an expert in microwave radar and a pioneer in optical communications. He worked at Bell Laboratories from 1941-1983 and passed away in 1990 [9].

with about a half dozen other summer interns working at Bell that year. Lau was assigned to help noted optoelectronics pioneer Joe Campbell (now at University of Virginia) who had a lab at Crawford Hill, which in addition to the fiber optics communication laboratory, also housed the radio communication laboratory directed by Arno Penzias. Located on a small hill behind the building is the still standing Hogg horn-antenna telescope that was used by Penzias and Wilson (1978 Nobel Prize in Physics) to discover the Cosmic Microwave Background [11], as well as by John Pierce for his pioneering Echo satellite trans-continental transmission experiments [7]. Campbell was trying to develop optical modulators based on electro-absorption. On his first day of work at Crawford Hill, Lau helped define his summer research task when he cranked up the voltage on the modulator so high it sparked and destroyed the best device Campbell had worked on all summer. As a consolation prize, Lau was assigned work on magneto-optic modulators – *it's harder to destroy a device with too much magnetic energy!* The summer proved to be as exciting as it was productive, and Lau was able to apply some of the phase matching techniques which Pierce used in describing traveling wave tube operation, to derive a set of discrete coupled mode equations for the analysis of the magneto-optic modulator he and Campbell were investigating. The summer's work led to his first journal paper [12], and his first patent [13].

Lau returned to Caltech in the fall as a senior and went back to working with Pierce. He applied to Caltech's graduate program, was quickly accepted, and intended to continue working on optical communications with the possibility of doing his thesis at Bell Labs. Pierce had made arrangements for Lau to pursue his PhD research in P.K. Tien's[7] laboratory at Bell Labs Holmdel when he ran into Amnon Yariv[8] in a hallway at Caltech. Yariv was aware of Lau's work on magneto-optic modulation with Campbell and wanted to convince Lau to stay at Caltech and work in his group on semiconductor lasers instead of going off to Bell. Between Yariv's pitch and the thought of being able to stay in sunny southern California versus the bleak, snowy New Jersey winter, Lau was convinced! He politely wiggled out of Pierce's group and joined Yariv's. It would be THE defining moment in his career.

At that time, Yariv's group was heavily involved in designing, fabricating, and testing semiconductor optoelectronics components and devices, with a major effort in laser diodes. They had their own liquid phase epitaxy crystal growth facility in the Caltech electrical engineering building (Steele) with a high temperature hydrogen purged liquid phase epitaxy system used by the students – something that would *singe* (raise) eyebrows today! They also had a lithography lab and could make sophisticated devices – their GaAs/GaAlAs lasers were already at the verge of operating continuously at room temperature, a state-of-the-art achievement at the time.

For the first few months of his graduate work, Lau learned how to grow crystals and fabricate the laser diodes. When Yariv was interested in moving on to high speed modulation of these devices for fiber optic communication, he appropriately tapped Kam for the project. The initial approach was straight forward and simply involved microwave signal injection into the laser diode device and modulation of the diode current. The problem was that no one in the lab at the time had the required microwave expertise or equipment. Fortunately, a professor from Iran's Shiraz University, Hossein Izadpanah, was visiting Yariv's group, and he came with a strong microwave background. Together, Lau and Izadpanah scrounged up some WW II surplus microwave generators and managed to perform some crude modulation experiments up to about 2 GHz. Unfortunately, Izadpanah took a trip back to Iran just before the take-over of the American embassy and the start of the US-Iran hostage crisis, and he was unable to return to Caltech.[9] Without a microwave expert in-house, and with limited test equipment, Yariv decided to team with a group at Hughes Research Laboratory (HRL) in Malibu, California that was working on laser diode mode locking. Kam linked up with HRL's Luis Figueroa[10] and together they performed a set of experiments on mode-locked semiconductor lasers which became part of Lau's thesis [17] and a number of publications [18]–[20] which followed his earlier magnetooptic modulator work with Campbell at Crawford Hill.

While Lau was working on his thesis with Yariv and HRL, he was approached by JPL's Ed Posner,[11] who wanted some help developing a fiber-based timing and frequency synchronization system for arraying widely spaced (10-20 km) large (up to 70m in diameter) antennas which were part of JPL's Deep Space Network (DSN). Posner hoped to very precisely disseminate ultra-stable atomic clock-derived time and frequency standards amongst multiple antenna stations for precision tracking and navigation functions (signals sent to-and-from a spacecraft and received at multiple antennas spaced tens of kilometers apart were used to exactly locate and track the spacecraft [22]). The technique required extremely precise (1 part in 10^{16}) RF phase stability for the microwave signals transmitted over the optical fibers that connected the widely spaced antennas.

[7] Ping King Tien was a former colleague of Pierce's at Bell and worked on microwave amplifiers before becoming head of the High Speed Electronics group and a Fellow of the Photonics Research Lab. He is best known for work on light wave propagation in thin films [14]. Tien died in 2017.

[8] Amnon Yariv, noted optoelectronics professor and National Medal of Science recipient (2010), had already come up with his pioneering concept of the semiconductor distributed feedback laser [15], [16] and his group was actively involved in diode lasers and optical communications technologies.

[9] Hossein was able to eventually make it back to the United States and ended up as a professor at University of Central Florida.

[10] Figueroa was extremely kind to Kam and offered to transport him the 80 miles back and forth between Caltech and Malibu during their collaboration at HRL and let him stay over at his house until Lau was able to afford a car of his own.

[11] Ed Posner is known for Posner's theorem in mathematics, coding theory, communications networks and computational neural networks. He was manager of JPL's Timing and Data Acquisition planning office, overseeing the operation of the Deep Space Network and later JPL's Chief Technologist. He was tragically killed in 1993 in a bicycle accident in Pasadena on his way to JPL [21].

Lau was still partially under the influence of his early yearnings to follow in the footsteps of Hsue-Shen Tsien, who had played a role in establishing JPL. He also had had a very positive experience a couple of years earlier when, while still working with John Pierce, Ed Posner had flown the whole group out to visit JPL's 64 m (now extended to 70 m) DSN antenna at Goldstone in the Mojave Desert on a JPL managed Lear Jet (*those were the days when scientists were appreciated!*). They even got to walk on the dish, as it was not being utilized at the time. Hence this JPL project was the realization of Lau's dream.

It took some convincing to get Yariv's permission for him to spend time on the JPL project, but Kam argued that the project was in line with his thesis and that JPL's state-of-the-art microwave equipment could prove a benefit for both his thesis work and for Yariv's group. Yariv consented, and Lau began working on the proposed DSN fiber synchronization system with JPL's George Lutes[12] over the summer of 1979.

Lau started by calculating the effect of cable bending (which would result from antenna movement while tracking spacecraft) on the phase stability of the transmitted microwave signals and found that the stringent phase stability requirements needed for tracking could be realized in principle [23]. Lutes made extensive measurements on temperature dependencies of the group delay in optical fibers. They concluded that their fiber synchronization system would be far superior to the best RF coaxial-based network, even with low-loss half-inch thick coax [24]. Lutes and Lau received a patent for this new RoF (radio over fiber, or if you prefer glyphs – most unusual in English – "RF" over fiber, with the "o" representing the fiber) application in 1981 [25].

Lau subsequently found a serious problem in the RoF system involving frequency dependent phase changes in the transmitted microwave signal when the fiber was bent. From his work at HRL on the effect of back reflections from external mirrors on laser diodes, he determined that the cause of the RF phase variation was due to slight defects in the quartz and short bends in the fiber optic cable that reflected small amounts of light back to the laser diode [26]. The problem could be corrected with an optical isolator, which became a standard feature in all subsequent RoF transmitters.

Throughout the remainder of his graduate career, Lau continued to work on his thesis at Caltech and shuttled over to JPL a couple of days a week to work with Lutes. Although the concept for the proposed RoF system at the DSN was established by their joint work in 1979-1981, it would take until the mid-1980s for the laser diode technology to be up to par (it would be Yariv's company, Ortel, at which Lau was founding Chief Scientist that first produced these devices), and a few more years until the actual fiber synchronization system was fully deployed at all three DSN complexes around the globe. In 1991, the value of this RoF system was realized when the main antenna on JPL's Galileo spacecraft failed to deploy on its mission to Jupiter, more than half a billion kilometers from Earth. An alternate, but much smaller low gain antenna, was to be used for all data transmission between the satellite and the ground stations. The weaker signal from the small antenna (and longer integration time this imposed on the receiver systems) meant that the data rate would have to be orders of magnitude below what the mission had planned for. The RoF links were used successfully to interferometrically array six separate DSN antennas significantly enhancing the gain and substantially reducing the integration time needed to process the spacecraft signals. This, along with additional data compression techniques, increased the data rate so that Galileo was able achieve more than 70% of its original mission objectives [27]. The complete DSN RoF system was later reviewed in a nice paper by Lau and his JPL colleagues [28].

These field-deployable ultra-stable RoF systems developed, demonstrated, and later commercialized by Lau and his JPL, Caltech and Ortel colleagues, were instrumental in the successful implementation of long distant time/frequency dissemination systems, critical not only to the operations of the DSN, but to radio telescope arrays worldwide, as well as to some important defense applications we will get to soon. RoF systems, like those deployed at the DSN, also provided the infrastructure for major commercial markets in cable and wireless internet that would reshape communications networks globally.

Lau finished his thesis work in 1981 and began looking for a permanent position in industry. He had decided it would be more advantageous (and lucrative) to establish a strong reputation in the commercial world before seeking an academic appointment. Amnon Yariv and Caltech's Bill Bridges[13] were role models here. While he was interviewing at Bell Labs, Lincoln Labs, HRL, Boeing, and many other places in the US, Yariv asked Lau if he might be interested in taking a position as the first employee of a new company that he (Yariv) was starting with promised venture capital funding from Warburg Pinchus in NYC,[14] to develop and commercialize laser diodes for the new microwave photonics industry. Company cofounder and a former student of Yariv's, Israel Ury, was already on board as President, and a post-doc of Yariv's, Nadav Bar-Chaim, was serving as vice-President. Yariv was the Chairman of the board. It was Israel Ury who ultimately convinced Kam to turn down his offers from more established institutes and take the riskier, but potentially more exciting role at the startup as its first official employee and Chief Scientist. Note that this was 1981, Apple Computer and Microsoft had just been founded a few years earlier, and in

[12]George Franklin Lutes, Jr. and his wife of 42 years, Juanita Chambless Lutes died of Covid 19 in December 2020 (Obituaries, La Canada Flintridge Outlook Valley Sun, La Canada, CA, pg. 4, Dec. 31, 2020).

[13]William Bridges is best known for his development of the argon-ion laser in the 1960's. Following a stellar career at HRL, he joined Caltech and became a professor in 1977. After helping build up JDS Uniphase he retired from Caltech in 2002.

[14]Henry Kressel, RCA researcher, *laser diode pioneer*, IEEE Centennial Medal and David Sarnoff award winner, and later managing director of the NYC based venture capital firm, Warburg Pincus, where he was on the board at the time.

this time period, joining a startup right out of school was a highly unconventional career choice.

Beginning in the fall of 1981, Ortel[15] started operating out of an empty warehouse in Alhambra, California about five miles from the Caltech campus. Israel, Nadav and Kam (with Yariv consulting approximately one day a week) began putting together the clean room, laser diode crystal growth facilities, lithography systems, fabrication, test and fiber assembly and packaging capabilities, lab benches and electronic test equipment, and every other article needed for a new venture starting up from nothing. A lot of time was also spent on business and planning activities. The seed funding of about \$1M had to last several years and mostly covered facility and operating costs, so product development was greatly aided by research contracts that the team was able to pull in from DARPA, the US Air Force, and the US Navy. The initial goal was to produce commercial quality laser diodes for RoF applications targeted at the phased array antennas and radar market (with aerospace defense contractors such as Raytheon potential major customers). Lau was responsible for high-speed laser analysis, design, and testing and he also doubled up as the company's sole electronics engineer: building the test systems and drive electronics for the laser diode characterization and reliability screening and any other custom electronics or test equipment that were needed. Through an understanding with Yariv, and thanks to the government research contracts at Ortel, Lau was able to moonlight at Caltech in the evenings and kept up with his research publications. During this period, he, Yariv, and other students of Yariv's, especially Chris Harder and Kerry Vahala, pushed forward the theory, technology, design, and operational limits of high speed directly modulated semiconductor laser diodes [29]–[34].

From the product development perspective, the major insight came in 1983 when Lau derived a simple formula for the laser modulation bandwidth f_r that involved only three basic parameters of the laser - the differential optical gain A, the photon density in the laser cavity, P_0, and the photon lifetime, τ_p: $f_r = (1/2\pi)\sqrt{(AP_0/\tau_p)}$ [29]. This derivation was much more intuitive and useful than the textbook formulation widely used as a standard up to that time, which involved multiple intertwined laser parameters: $f_r = (1/2\pi)\sqrt{[(J_o/J_{th}\text{-}1)/(\tau_{spon}\tau_p}$], where J_o and J_{th} are the bias current and threshold current of the laser diode respectively, and τ_{spon} is the spontaneous lifetime of the carriers in the active region of the laser.

It was Yariv that realized the AP_0 term was the inverse of the stimulated carrier lifetime, τ_{stim}, so that the bandwidth could be expressed as: $f_r = (1/2\pi)\sqrt{[1/\tau_{stim}\tau_p)}$], the inverse of the geometric mean of the photon and stimulated lifetimes, which made a lot of physical sense. Lau's simple formulation made it straight forward to design a laser diode for maximum modulation bandwidth by independently optimizing each of the three physically accessible parameters of the laser. As the direct dependence of modulation speed f_r on differential optical gain A was not previously known, this assertion was verified through a low temperature measurement that Lau carried out with Chris Harder and Yariv [30]. They recorded that f_r increased as the temperature dropped, as predicted by Lau's formula, although they could not get good modulation data below 220 K because of increased series resistance in the diode due to carrier freeze out. However, a few years later Caltech's now Professor Kerry Vahala, and his student M.A. Newkirk, were able to make modulation measurements down to 4 K by using a photomixing optical modulation scheme that did not suffer from carrier freeze out and demonstrated increased rates out to 37 GHz [35], affirming the relationship between f_r and differential optical gain that Lau's formula had predicted. Additional improvements in f_r could also be made with one dimensional lasers (quantum wires) created by a high B field, demonstrating quantum confinement effects [31].

This fundamental understanding of the relationship between modulation speed and laser diode parameters, plus the now well-developed GaAs/GaAlAs laser fabrication and microwave injection techniques, allowed Ortel to very quickly develop and sell RoF laser transmitters that could exceed 10 GHz [32]. There was no commercial competition at the time (it would take 10 more years for equivalent speed external optical modulators to come on the market), and although GaAs/GaAlAs lasers operating at wavelengths of 800/850 nm were not optimal for long distance telecom fiber transmission (spanning hundreds of kilometers), there were still applications for Ortel's RoF devices in several niche markets.

One of the first major customers of the Ortel RoF devices was the nuclear weapons testing community under the US Dept. of Energy [36]. It turned out that monitoring underground nuclear bomb tests took a heavy toll on the data collection sensors – *they were literally vaporized within a few microseconds of detecting the heat, pressure, and radiation they were designed to monitor*! The precious data detected by each of hundreds of sensors buried deep underground had to be transmitted to recording equipment (ultrafast single-shot streak cameras) placed above ground and more than 1 km from the blast site before *everything* was vaporized! In addition, the relevant signals were of sub-nanosecond duration, had varying amplitudes that spanned orders of magnitude, and it was necessary to record the precise signal pulse shapes to properly analyze the nuclear tests. Finally, since the blast event was a very expensive one-shot opportunity, no signal averaging techniques could be employed. Taken together, these were extremely demanding requirements.

The RoF fiber network offered by Ortel had great advantages over the existing coaxial line linked sensor arrays that were deployed at the time. These suffered from lower bandwidth and were susceptible to interference from the enormous electromagnetic pulse (EMP) that accompanied the nuclear blast. The RoF links were much faster, were not affected by the EMP, and even the 850 nm wavelength of the GaAs/GaAlAs lasers (which already stated, was not ideal for long distance fiber applications) was an excellent match to

[15]Ortel stems from the Hebrew "אור" (or) meaning light, and "תל" (Tel) meaning mound or hill, hence Ortel=Hill or Mountain of Light.

the shorter-range blast monitoring stations and to the streak cameras used to record the transient data and which had their highest sensitivity around 800 nm.

Using Ortel's lasers and fiber links to implement this unique data capture application resulted in an order of magnitude improvement in the temporal resolution of the acquired signals over all prior coaxial cable systems. Lau was invited to attend the system design workshops and collaborated with scientists and engineers from all three US national nuclear weapons laboratories (Lawrence Livermore, Los Alamos, and Sandia). Together, they successfully adapted their RoF data capture system to compensate for the inherent frequency dependent laser distortions, and were able to record details of the nuclear blasts that had never been seen before. The enhanced diagnostics led to rapid advances in the US strategic weapons program and played a role in the US-Soviet arms agreements pursued during the Reagan Presidency.

The US Department of Energy might have been a long-term customer, and a good one at that, since every laser Ortel sold to them was vaporized in short order in the Nevada desert, prompting additional follow-up orders! However, the political climate at the time favored nuclear disarmament by the superpowers and with a comprehensive test ban treaty looming on the horizon, Ortel began turning its attention to other applications for its high-speed lasers and RoF links. It was at this time that significant orders from JPL's DSN program began to arrive, for deployment of the ultra-stable frequency/timing fiber dissemination system that Lau and George Lutes had worked on in the early 1980s. Other major radio telescopes around the world, as well as military radar installations, also began to install these RoF networks, all of which benefitted from the improvements Lau and colleagues at Ortel and Caltech had been continuously making in the quality, bandwidth and performance of the laser diodes [37]–[39].

The real "killer" market for RoF transmission systems didn't materialize until after Hank Blauvelt joined Ortel. Blauvelt was a former student of Yariv's and a lab mate of Lau's at Caltech. He came to Ortel from HRL in 1984 and was followed shortly after by his spouse, Caroline Gee, an expert in microwave fiber optic transmission, and two other alumni from Yariv's group, P. C. Chen and T.R. Chen. Together with Blauvelt, they began developing high speed long wavelength quaternary distributed feedback (DFB) lasers and detectors based on GaAlAsP and detectors that were better aligned with low loss, low dispersion fiber transmission at 1.3 and 1.55 microns. At the same time, compact, hermetically sealed transmitter and receiver modules were developed by the Ortel packaging team.

The marketing group started taking these new products to industry shows, one of which happened to be (on a whim) the Western Cable Show.[16] Cable TV operators at the time were planning to upgrade their existing networks by adding RoF links to improve the transmission distance and reliability of their then all-coax configurations to be able to deliver the then new high-speed internet services to homes and businesses. For the long reach trunk lines (>50 km) from "headends" (the receiving station where TV signals are processed, inserted, and distributed over the network) to major distribution hubs, they needed high power laser transmitters with linearized external modulators. The Cable TV bandwidth was large (55–650 MHz) and there were very stringent requirements on the signal quality, which the external modulators could meet. United Technologies Photonics, Bloomfield, CT, was amongst the first suppliers during the early 1990s, but these systems were very expensive. A cheaper solution was needed for the by-far more numerous short reach networks that fed off the major hubs and connected to localized nodes before switching over to coaxial cable for the remaining "last-mile" that reached out to individual customers.

Directly modulated laser transmitters, Ortel's bread and butter, were desirable for these short reach RoF links, but the same stringent performance requirements levied on the long reach links, which used expensive externally modulated laser transmitters, had to be satisfied. Extensive testing of existing state-of-the-art directly modulated laser diodes revealed an intermodulation distortion level significantly higher than that required for CATV transmission. All attempts at Ortel to reduce this distortion by improving the laser diode structure had proved ineffective. Lau had investigated this problem in 1984 with GaAs/GaAlAs lasers and had concluded that the fundamental mechanism generating these intermodulation distortions was none other than stimulated emission, the very process responsible for laser action [33]. Even in the absence of any other imperfections, the level of this fundamental signal distortion was already 38 dB higher than what was required for CATV transmission, and it could not be eliminated by creative device design. Eventually, Blauvelt teamed up with Ortel's electronics guru Howard Loboda (later founder of OnePath Networks), to develop a compact predistortion circuit that they were able to incorporate into the laser transmitter module and that precisely compensated for the distortions [40]. This task was made easier by the relatively flat frequency dependence of intermodulation distortions in the CATV band, made possible by Ortel's high speed laser designs as prescribed by Lau [33].

Intermodulation distortion was not the only issue preventing low cost directly modulated laser diodes from being used in the CATV networks. For the shorter distances (<50 km) used in the hub networks, it was thought that simple cleaved facet Fabry-Perot (FP) lasers could serve as suitable transmitters, rather than the more complex distributed feedback (DFB) devices used in the long-haul links. However, Lau and Blauvert discovered that these FP laser diodes generated a new type of noise arising from mixing of the high frequency CATV signals with low frequency "mode partition noise" (jitter) typically found in FP lasers. The resulting intermodulation products appeared in the CATV band and significantly reduced the signal-to-noise margins [41]. Together with his

[16]The Western Cable Show, sponsored by the California Cable & Telecommunications Association, ran from 1967 to 2003 and was one of the largest trade shows in the cable industry.

Ortel colleagues, Lau performed detailed measurements and analysis of RoF links using both FP and DFB lasers [42], and concluded that only the DFB lasers would work for the CATV transmitters, not because they were less susceptible to fiber chromatic dispersion as in long distance telecom links, but for avoiding the excess mode partition noise inherent in the FP lasers. Fortunately, Ortel had already mastered the production of 1.3 and 1.55 micron DFB lasers through the earlier efforts by Blauvelt, T.R. Chen, and P.C. Chen and other members of the laser fabrication team.

The company thus had all the pieces in place for meeting the stringent distortion requirements and cost targets of directly modulated laser transmitters for the CATV industry. Cable infrastructure hardware manufacturers including General Instruments, one of the largest in the cable industry, came calling, and by 1995 Ortel had grown to the point of going public. After five years as a public company, Ortel was acquired by Lucent in early 2000 in a deal worth 2.95 billion dollars [43]! It was then spun off as a division of Emcore Corporation, which remains today a dominant RoF hardware manufacturer for the cable and satellite communications industries – all based on the developments pioneered by the co-founders and early employees of Ortel in the 1980-90s. Even today, Emcore's web site still proudly advertises "Genuine Ortel Technology" [44].

While all this shift to providing RoF capability for the cable industry was evolving, Ortel began expanding rapidly, boosting its manufacturing capacity to satisfy the rising industrial demands. In 1988, after 7 years with the company – starting from its very first day - Lau felt it was time to do what his Caltech mentors had done and move to academia. During his entire time at Ortel, even after 1984 when it began to grow, he had maintained a continuous stream of quality research papers working both with Yariv and his group at Caltech, as well as with individuals at the company. When Kam started to look into faculty positions in 1988, he received several offers in short order, and accepted a position as Associate Professor at Columbia University in NYC. He moved to suburban Armonk, NY (near IBM headquarters) in the fall of 1988, and took up the daily hour-long commute into Manhattan to start his teaching career (*a far cry from the days he had to rideshare with Luis Figueroa in order to commute to HRL*).

At Columbia, Kam quickly formed a research group and focused on quantum well laser modulation dynamics collaborating with colleagues at IBM Watson Research Center in Yorktown Heights, close to his home in Armonk. At first, he continued work he had started just before leaving Ortel [45], moving into system aspects of CATV/cable-based internet transmission [46]. Through bi-weekly consulting trips to Ortel, he also continued his collaborations there, while directing his Columbia students in quantum-well lasers and wavelength-division multiplexing (WDM) network research [47]–[58]. However, after two brutal winters and frequent trips to Pasadena and Boston (for consulting), life in NY took its toll. I asked Kam if he at least enjoyed taking advantage of all the social and entertainment venues available in New York City, thinking it might have made up for some missed experiences from his youth in Hong Kong, but he said he rarely saw anything beyond the two square blocks between 118th and 120th streets, and Broadway to Amsterdam Avenue, that define the Columbia campus – arriving in the 120th street parking garage below the EE department's Mudd building in the morning, and exiting his car at his Armonk home in the late evening. It should be no surprise that when John Whinnery[17] phoned in late 1989 and told Lau that the new department chair at Berkeley (David Hodges[18]) was interested in having him come out to Berkeley to interview for a full professor position, he jumped at it. After receiving the offer from Hodges, Kam packed his bags, discarded his winter clothes, and moved back to California in 1990!

At Berkeley, Kam continued to expand his group – reaching 16 students plus an additional 2-3 post-docs at one point – and while still maintaining his work on high speed quantum well devices [59]–[63], he broadened his research to millimeter-wave transmission over fiber [64], [65], expanding on some of his earlier developments at Ortel [47], [53]. Around 1994, he also teamed up with his Berkeley colleague, Professor Richard Muller, a pioneer in Microelectromechanical Systems (MEMS), to launch a new effort at Berkeley in micromachined optical systems [66]–[74]. In addition to the wide variety of laser topics he was exploring with his students, Lau also started thinking again about RoF applications, mainly with two students, John Georges and David Cutrer, who would end up being critical to his next big venture.

The electrical engineering building at Berkeley (Cory Hall) is typical of many older buildings that are mainly of rebar and concrete construction (metal mesh), through which radio waves do not easily traverse, particularly in the lower floors and basement levels. These areas were continually plagued by poor to non-existent wireless reception. The communications industry was well versed in distributing strategically placed antennas in outdoor spaces to reach "hard to get to locations" and Lau realized this same approach, coupled with RoF, might be used very effectively to construct a "Distributed Antenna System" to extend radio coverage to every nook and cranny within buildings, where it was often impossible to connect multiple floors and offices to a roof antenna without kilometers of lossy RF cable. Lau and his group, especially Georges and Cutrer, began experimenting with a novel RoF application to provide complete wireless coverage in Cory Hall [75]–[78]. They connected an RoF link to a well-placed roof antenna, running the fiber down through the cable chute inside the building core, and then distributing to a network of antennas on every floor and in hard-to-get-to rooms with

[17]John Whinnery of Ramo, Whinnery and van Duzer, "*Fields and Waves in Communication Electronics*," was a long-time faculty member and microwave expert extraordinaire at UC Berkeley (1946-1987), and Amnon Yariv's thesis adviser in the 1950's. A National Medal of Science winner (1992), amongst many other awards, he passed away in 2009.

[18]Dave Hodges is best known for his work with Berkeley Professor Paul Gray on MOS circuits and for the development of computer aided manufacturing of CMOS integrated circuits chips widely used in today's silicon industry.

coax cables - a form of hybrid fiber/coax network that Lau had worked on extensively at Ortel back in the 1980s. The system worked beautifully [77], [79]! They expanded the concept to utilize Cat-5 cables for the signal distribution within floors, since Cat-5 is a ubiquitous infrastructure that already exists in almost all office buildings thus bypassing the need, and the significant cost, of laying new cables.

Based on their positive results in the field trial of their RoF system in Cory Hall, Lau (L), Georges (G) and Cutrer (C) co-founded LGC Wireless in 1997 with funding from prominent venture capital firms, led by Mayfield Fund in Silicon Valley. Simon Yeung, another student in Lau's group who had recently arrived from Purdue, joined this research effort at Berkeley, and upon receiving his M.S., he signed on as LGC's first employee, becoming a valued and principal member of the team. The concept was an instant success, allowing wireless coverage and broadband voice/data over-internet access in what were formerly hard to reach places inside buildings. The market was huge and in short order LGC had established their leadership role. More than 10000 systems were shipped and installed worldwide in more than 100 countries, providing wireless coverage and capacity solutions for providers and the enterprises alike. Major landmark installations include the 88 story, 450m high Petronus Twin towers in Kuala Lumpur, Malaysia, the 830m high Burj Khalifa in Dubai (currently the world's tallest building), and even the FCC headquarter in Washington DC. Cruise lines were also major customers as RoF was ideal in distributing radio signals into the solid metal boxes that comprise cruise ship cabins!

For LGC Wireless, Kam took on the role that Yariv had played for Ortel and became chairman of the Board as well as a consultant/adviser while he continued with his teaching and research work at UC Berkeley. Although he was instrumental in securing the early funding for LGC, and for the first 3 years of its existence handled many of the tougher senior management decisions, as with Ortel, he did not stay on for the acquisition phase, although this time for an altogether different reason, which we will detail shortly.

LGC was acquired in 2007 by ADC Telecom for \$170M and it is now a division of TE Connectivity. After the acquisition, John Georges and David Cutrer teamed up again to form NextG Wireless, a company that took advantage of unused dark fiber capacities in existing infrastructures to rapidly and cost effectively deploy broadband wireless communication capabilities where none existed before. In 2012, they sold NextG to wireless infrastructure giant, Crown Castle, for more than \$1B![19] John Georges is now a senior advisor at QMC Telecom while David Cutrer has been tapped to become the CEO of yet another startup in the Bay Area, Kumu Networks. Simon Yeung went on to become President and executive chairman of Comba Telecom, a major publicly listed wireless infrastructure company in Hong Kong.

Early in 2001, Lau suffered a serious seizure which put him in the hospital. After a CT scan he was told that he had a congenital birth defect – an arteriovenous malformation (AVM) – a brain malady that is characterized by malformed arteries and veins that can disrupt blood flow, with the possibility of bursting at any time and without warning, causing a massive stroke or even death. Lau was hesitant to undergo the intrusive and risky surgical procedures necessary to remove the AVM, but to just live with the condition, waking up every morning and not knowing if the day would be his last, was not something he wanted for the rest of his life. Around the time of Thanksgiving 2001, he went in for a complex and lengthy surgery to seal off the arteries feeding the AVM and resect the blood vessel entanglement. The operation was complicated by the fact that he had to have the surgery in two different hospitals – as a direct result of the complicated medical insurance system in the US – and when he finally recovered sufficiently from the cranial incursions (requiring three subsequent surgeries to clean up the infections), he was paralyzed on his left side and confined to a wheelchair.

One cannot imagine the blow this caused to Lau's psyche, not to mention the physical discomfort and hurdles he was facing just to maintain any semblance of a normal life going forward. He heroically managed to stay at Berkeley for another four years, before retiring in 2005. Lau refused to let his situation completely hobble him however, and he has since managed to complete a comprehensive textbook on his years of developments in RoF [80], which he soon after revised and expanded to a second edition [81]. He also wrote up two extensive invited papers, one on the work that led to LGC [79] and the other with his long-time colleague and friend from his graduate student days, George Lutes at JPL, to help summarize many years of success employing RoF in the space science and radio astronomy communities [82].

Speaking with Kam Lau and listening to his many stories was both interesting and inspiring. His extreme focus on work, his incredible productivity, and his remarkable talents – for art, for engineering, for business, for community - showed that his 43 years of healthy and unencumbered existence are the equivalent of what one might hope to accomplish with twice that much time. I hesitate to predict what more he would have undertaken without the intervention of AVM, but he has already contributed more than enough!

SUBJECT BIO

KAM-YIN LAU (Fellow, IEEE) is Professor Emeritus in the EECS Department at U.C. Berkeley. He received his B.S., M.S., and Ph.D. degrees in 1978, 1978, and 1981, respectively, all in Electrical Engineering from the California Institute of Technology, Pasadena, CA. He was founding staff/chief scientist at Ortel Corp., Alhambra, CA, from 1981 to 1988, an Associate Professor of Electrical Engineering at Columbia University from 1988 to 1990, and a Professor in the EECS Department at U.C. Berkeley from 1990 - 2005. In 1997 he co-founded LGC Wireless and served as its chairman until 1999. He assumed Professor Emeritus status at U.C. Berkeley in 2005.

He has received numerous recognitions for his work on high-speed laser diodes and RF-over-Fiber transmission that has had significantly impacted

[19]Georges and Cutrer gave a presentation at U.C. Berkeley in 2019 describing their entrepreneur ventures and how their experiences at LGC led them to adopt a new business model for NextG that resulted in its exceptional valuation: 20x of revenue instead of the customary 2x. They proved to be as savvy in business as they are in engineering! https://www.youtube.com/watch?v=74nmJnWO7Qw

cable and wireless internet access, as well as aerospace and defense systems. They include the 2021 Microwave Pioneer Award from the IEEE MTT-S, the 2013 Pioneer Award from the IEEE Aerospace Electronic Systems Society, the 2009 David Sarnoff Award from the IEEE, the 2009 J.J. Thomson Medal from the IET (U.K.), and the 2011 Benjamin Oliver Gold Medal for Engineering from the Armed Forces Communications and Electronics Association (renamed in 2012 as "Distinguished Award for Excellence in Engineering").

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