Terahertz Pioneer: Paul L. Richards

Working at the Edge—Transition Edge Sensors and the Edge of the Universe

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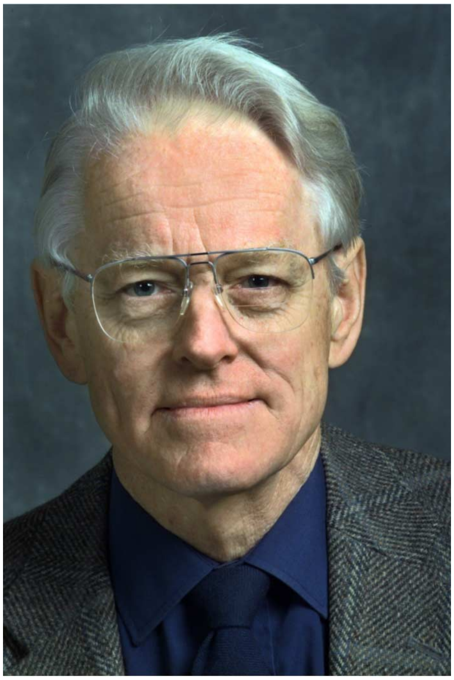
AS THE SON of Lorenzo A. Richards [1], a well-known physicist, and pioneer in Soil Physics, and with seven uncles holding Ph.D. degrees, perhaps it was inevitable that Paul Linford Richards[1] would find himself choosing a career in science. However much this may have been favorably influenced by his relationship with his family, it was not forced upon him, for as he told me, his father insisted that he, Paul, spend appropriate apprentice time with individuals practicing alternate professions before he chose to enroll in Harvard and to begin a long and stellar career in physics. We should all be very happy that his own force of will, innate talents, and strong desire to take the path less trodden, placed him in a position to have such a profound and widespread impact on Terahertz science and the instrument and device technologies that are so commonly employed today throughout our field.

As a child, Professor Richards had access to his father's shop and home laboratory and quickly learned how to make things for himself. He is still making things, but now they involve multimillion dollar telescopes and receiver packages that go beyond the visible universe and peer into our cosmic origins. The road from university student to distinguished Professor at the University of California Berkeley has not always been a smooth one, but it is certainly one that can provide some insight for those who hope to follow a similar path. It took Professor Richards through three careers in—condensed matter spectroscopy, high frequency detectors, and finally, cosmology. All were linked through an uncanny ability to understand the essence of the instrumentation needed to extract the science—a gift that Professor Richards credits to his training in both microwaves and far-infrared techniques that began with an extraordinary undergraduate course on electromagnetic waves at Harvard taught by Professor Edward Purcell, recipient of the 1952 Nobel prize for the discovery of nuclear magnetic resonance.

After graduating Harvard College in 1956, Mr. Richards decided to come back to California—he had spent much of his youth in Riverside—and he enrolled in the Ph.D. program at the University of California, Berkeley, to do Solid-State Physics. His attraction to Berkeley was in part due to a recommendation by Harvard Professor Nicolaas Bloembergen (Nobel Prize in Physics 1981). At Berkeley, Richards hooked up with Professor Michael Tinkham, who was working on superconducting thin films. Tinkham was trying to measure the recently predicted Bardeen-Cooper-Schrieffer (BCS) theory [2] energy gap, which was a very hot topic in condensed matter physics. The frequency range for the measurements was in the millimeter and submillimeter-wave regions and the most sensitive detectors at the time were Golay cells, which had to be used outside the cryostat and had noise equivalent power in the nanowatt/root hertz range—insufficient for the measurement with the then currently available black body sources and grating spectrometers. Fortuitously, Richards received a preprint about some new carbon radio resistor bolometer work by Willard Boyle [3] (better known for his work on CCD devices for which he recently received the 2009 Nobel prize in Physics), wherein the change in resistance versus temperature of material from a helium cooled carbon resistor was used as a very sensitive bolometric direct detector, *inside* the cryostat. Using this bolometer, Richards quickly (3 weeks!) put together an instrument that successfully measured sharp energy gaps of a wide range of



PAUL L. RICHARDS

Manuscript received August 25, 2011; revised September 10, 2011; accepted September 11, 2011. Date of current version October 28, 2011.

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Digital Object Identifier 10.1109/TTHZ.2011.2168998

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[1] Paul L. Richards has made Berkeley, California his home for more than 45 years. He is currently Professor of the Graduate School in the Department of Physics at the University of California Berkeley. Between brief sojourns into the chemistry of wine making, he continues to work with students, to be heavily involved in major new programs in cosmology (Polarbear), to write and to lecture. I met him at his lovely home in the Berkeley hills for this interview, which was conducted on August 5th, 2011.

bulk superconductors [4], [62], verifying the BCS theory, and resulting in some of his most widely cited publications.

This very rapid experiment-to-publication experience had Dr. Richards out of Berkeley with a Ph.D. in only three years. In 1959 he was off to Cavendish Laboratory, Cambridge, U.K., under a National Science Foundation Post-Doctoral Fellowship to work with noted physicist Sir Alfred Brian Pippard on measuring the surface impedance of superconductors in magnetic fields using microwave techniques [5]. At Cambridge, Dr. Richards found that the pace of his experimental developments was somewhat hindered by rules dictating who had access and priority in the fabrication shops, nevertheless he managed to link his detector experience with his microwave work in Pippard's group, and set the stage for his future career path.

Dr. Richard's returned to the U.S. in 1960, to take up a pre-arranged post at Bell Laboratories, working in John K. Galt's group (later director of Sandia National Laboratory), afterwards led by Solomon J. Buchsbaum (Medal of Science recipient and Executive Vice-President at AT&T). The work was focused on measuring properties of solids at low temperatures. Richards began by building a cryogenic bolometer and vacuum grating spectrometer that he used to confirm Philip Anderson's (1977 Nobel laureate in Physics) theory of dirty superconductors. Shortly afterwards he greatly improved his millimeter-wave spectroscopy by substituting a Michelson Interferometer for the grating [6]. Again, Dr. Richard's "hands on" background served him extremely well. He realized that by automating the data collection and analysis he could vastly speed up his measurements, so he interfaced his spectrometer to one of the early computers being used by the UNIX development group at Bell. He put together a homemade voltage-to-frequency converter, counter and card punch that produced the data input cards required by the computer. With this novel "automated" Fourier Transform spectrometer, and Boyle's high sensitivity cryogenic carbon resistor bolometer, he had an instrument that, like his graduate student days, was unique in the world.

As might be expected at a place like Bell in the 1960s, there were lots of people who had materials they were interested in characterizing in this underdeveloped frequency range. He published spectroscopic measurements on superconductors, semiconductors, ordered magnetic insulators, and unusual phonon systems. He also did electron spin resonance in hemoglobin and made a superconducting point contact direct detector for millimeter waves based on the Josephson effect [7], [8], which would later become a major career path diversion. One ambitious experiment that didn't work was a collaboration with Princeton Professor Phillip Anderson (then at Bell, and winner of the Nobel Prize in physics in 1997) to search for the Josephson effect in superfluid helium [9].

After 6 years at Bell, Dr. Richards felt he was beginning to get pigeonholed into a career path he was not so enthusiastic about, and his interests had expanded so much that he was looking for a way to start up his own research group. University positions were a natural choice, and even though he had several offers, he was drawn again to Berkeley, which had a very strong group of experimental solid-state physicists who worked on measurements of fundamental physical phenomena and apparatus development.

Richard's crossed the country in late 1966, and arrived at Berkeley hoping to take up again with Mike Tinkham. However, Tinkham was off to Harvard, and Raman spectroscopy was just coming of age, making Richard's Fourier Transform spectrometer measurements far less unique. Although the young Professor Richards continued his work on the FTIR as well as with the newly established Josephson detectors, he was open to yet another change in his research path. This came around 1970, when Professor Charles Townes (1964 Nobel Laureate in Physics) told him about some interesting discrepancies in the measurements of the Cosmic Microwave Background (CMB) spectrum. There was some suggestion that narrow spectral features were being red shifted into the millimeter-wave band and appearing in the CMB blackbody spectrum. Townes thought Richard's background in millimeter wave spectroscopy, coupled with his gift for developing state-of-the-art instrumentation, might be a good match for the difficult problem of resolving the controversy over the cosmological implications of the observed spectral distribution of the highly red shifted energy signature left over from the Big Bang. One of Townes' post-doctoral researchers, Dr. Michael Werner (currently Chief Scientist for Astronomy and Physics at the Jet Propulsion Laboratory, Pasadena, CA, USA), and a new student at Berkeley, John C. Mather (later, 2006 Nobel Prize winner in Physics and Chief Scientist at NASA) teamed up with Professor Richards to begin looking at ways to accurately measure the CMB spectrum in the critical millimeter-wave region. Richards realized that a scanning narrow band Fabry–Pérot and fast Putley detector was the right instrument to do a ground based experiment. They measured their first spectrum in 1971 at the UC Berkeley Barcroft Laboratory White Mountain observatory in eastern California [10], finding no identifiable primordial spectral lines, but making some of the first accurate measurements of atmospheric oxygen and water vapor in the 150–400 GHz frequency range [10].

At this time, Professor Richards was providing laboratory facilities and advice to germanium expert, Eugene E. Haller, Berkeley Professor of Materials Science (then at Lawrence Berkeley National Laboratory), to interest him in the needs of the infrared astronomy community. Haller developed improved technology for the germanium–gallium (GeGa) detectors on the NASA Infrared Astronomy Satellite (IRAS, launched in 1983) and the NASA Spitzer space telescope launched in 2003. At Richards' request, he developed neutron transmutation doping, and produced well characterized thermometer chips for essentially all of the world's composite and spiderweb Ge bolometers, including those on the European Space Agency's Planck and Herschel spacecrafts, launched in 2009. Richards collaborated with Haller to produce the first stressed Ge photoconductors, which extended the low frequency cutoff of photoconductivity in Ge from 2.2 to 1.5 THz [11], [12]. This lower frequency capability was used on numerous aircraft, balloon and rocket experiments and provides the long wavelength band for Spitzer.

For improved CMB spectrum experiments however, Richards realized that significantly better millimeter wave detectors were needed. Although the heavily doped and compensated germanium bolometer worked very well at shorter wavelengths, it did not absorb millimeter waves effectively. Richards thought back to his days in the Purcell electromagnetic waves class at Harvard, and recalled that thin-film absorbers were routinely used in the microwave bands to match both free space and waveguide modes. In order to produce an absorber with low heat capacity at low temperatures, he chose to evaporate a very thin bismuth film on a thin sapphire substrate and to attach a thermometer to make a *composite* bolometer. This idea was then tried in a bolometer with a superconducting transition edge thermometer (*transition edge sensor*), developed in collaboration with Berkeley colleague Professor John Clarke [13], [14]. A more practical configuration of the composite bolometer, which used a chip of doped germanium as the thermometer [15], became the key enabling detector technology for an entire branch of modern cosmological science and for a suite of critical millimeter and submillimeter wave astrophysical observations from the ground, high altitude aircraft, stratospheric balloons, suborbital rockets and orbital platforms.

With the detectors in hand, the ability to accurately measure the CMB spectrum became a dominant research thrust for Professor Richards and his Berkeley students. Unfortunately the science funding agencies were not so accommodating, having already committed to a high visibility spacecraft to measure the CMB. This did not deter Richards however, who managed to secure a battered balloon gondola from the Berkeley Space Science Laboratory, and along with John Mather and student Dave Woody (currently Assistant Director of the Caltech Owens Valley Radio Observatory), put together their own CMB radiometer to measure the 3 K blackbody spectrum. After several early attempts [16]–[18], the key experiment flew in 1979 out of the U.S. National Balloon launch facility at Palestine, TX [19]. This was the most complete CMB spectrum that had ever been measured and generated hundreds of theoretical papers, especially on the trends that showed up on the high frequency side of the blackbody peak, where the power spectrum begins to roll over.

Despite their success, funding for more CMB work was simply not available to the Berkeley balloon team, while the science community waited for the NASA Cosmic Background Experiment (COBE) space mission. Professor Richards went back to detector development and hoped to do for heterodyne detectors, what he had already done for the direct detector community. He picked up on point contact Josephson junctions, which he had previously used as direct detectors. Teaming with post-doc Dr. John Claassen [20]–[23] and student Yuan Taur [24]–[30], they worked out the theory and did the first experiments on Josephson junction mixers in the millimeter wave band. Although much was learned, and there was some great science, ultimately the Josephson junction did not work well as a heterodyne element, mainly due to parasitic conversion from higher harmonic frequencies.

Going back to basics, and looking closely at what was really needed to make an ideal mixer for the millimeter- and submillimeter-wave bands, Richards realized that thin-film tunnel diodes made with a superconductor–insulator–superconductor (SIS) sandwich, produced the fast switching behavior (sharp current–voltage knee) that was required. Junctions of this type, called thin-film Josephson junctions, were widely used near zero bias to explore the effects of Josephson (pair) tunneling. In the mixer application, the junction was biased near the energy gap voltage so that single particle (quasi-particle) tunneling dominated, as was first studied by Ivar Giaver (Nobel Prize shared with Brian Josephson and Leo Esaki in 1973). Using simple lead and lead -alloy films, that were overlapped to form native oxide barriers (obtained from collaborators at the National Institute of Standards, Boulder, CO), Richards and student T. M. Shen tested the first SIS quasi-particle mixer in 1978 [31]. He then went on with additional collaborators to explore the very interesting physics of this device [32]–[37]. A theoretical analysis of the quantum contributions to the mixing process by University of Illinois Professor John Tucker (then at Aerospace) [38] predicted net conversion gain and noise at the quantum limit. The Berkeley group observed both of these effects in excellent agreement with theory. The lowest noise mixers required tunnel junctions which had very sharp current-voltage knees. Collaborator Dan Prober at Yale produced the tunnel junctions used by the Berkeley group to achieve their best results [39], [40].

Publication of the first SIS mixer test results from both Berkeley [31] and Caltech Professor Tom Phillips's group [41] (then at Bell Laboratories), and the early deployment of a successful receiver by the Caltech team on an Owens Valley telescope and later in NYC and the mountains of Chile by a Columbia/NASA team [42], caused tremendous excitement in the community building heterodyne receivers for radio astronomy. Major development efforts began in many laboratories, which, over the last 30 years have resulted in well-coupled, broadband, low noise SIS mixer receivers with practical cryogenics over the frequency range from 90 to 1200 GHz at observatories world wide as well as in outer space.

Although it is difficult to credit any individual alone for the SIS mixer revolution, it is fair to say that all the individuals mentioned above and their research teams gave birth to, developed and initially optimized this unique and now ubiquitous detector concept. Together they revolutionized low-noise millimeter- and submillimeter-wave heterodyne receivers. SIS mixers have been used in almost every ground-based millimeter-wave astronomical observatory, from Europe, Russia, Japan, and the Americas, to the South Pole and now in China. They have been carried on stratospheric balloons in both hemispheres and around the South Pole. They have performed beautifully on stratospheric aircraft and have even flown in space on both a THz orbital observatory (ESA's Hershel Space Telescope) and on the International Space Station (Japan's SMILES instrument).

Having launched both new, direct and heterodyne THz receiver technologies, Richards again was drawn back to the CMB measurements. Meeting up with a new and talented student, Andrew Lange, Richards decided to team up with a Japanese group that was interested in fielding a suborbital rocket. This collaboration, with S. Hayakawa and T. Matsumoto [43], [44] had the Berkeley team supplying the detectors to the payload that was assembled and launched in Japan. There were three flights over a multiyear period, of which two returned useful data. In the second flight, spurious pickup led to a report of excess radiation in the 200–300 GHz range where the 3 K blackbody signal is very small. This pickup was missing from the third flight, but the team could not agree on publishing a retraction. The final word ended up going to the NASA COBE team led by John Mather, who shared the 2006 Nobel Prize in Physics for the measurement of the spectrum.

The experiment on COBE led by George Smoot, who shared the 2006 Nobel Prize with Mather, measured the weak angular anisotropy of the CMB which arises from quantum fluctuations in the very early universe, at an angular scale larger than 10 deg. Theory predicted that these primordial anisotropies on smaller angular scales, would have evolved in time under the effects of gravity and radiation pressure, and would contain a tremendous amount of information about the composition of the early universe. At this time, the National Science Foundation (NSF) funded the Center for Particle Astrophysics which allowed resources to reach the Berkeley balloon group. Having waited for this opportunity for several years, Richards and Lange quickly put together a CMB package for measuring the 1-degree scale anisotropy and flew five flights out of Palestine, Texas, testing new detector and balloon cryogenic receiver technologies. These initial flights led to the design and implementation of Professor Richard's most successful experiment to date, Millimeter Anisotropy Experiment Imaging Array (MAXIMA) [45]–[47].

MAXIMA contained a focal plane array of 16 bolometers, feed horns, bandpass filters and readout circuitry operated at 100 mK with an adiabatic refrigerator designed by Richards himself. At the same time Paolo de Bernardis of University La Sapienza, Rome, Italy, suggested a collaboration to field a MAXIMA-like instrument at the South Pole, where, due to the wind patterns, an observation run around the Pole could last 10 days or more. The collaboration was taken up by Andrew Lange as the Berkeley PI, and Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics (BOOMERANG) was born [48].

The large flux of cosmic rays near the south magnetic pole forced a change in bolometer architecture that was started at Berkeley [49] and later perfected and produced by a team at the California Institute of Technology, Jet Propulsion Laboratory, Pasadena, CA [50]. Instead of a continuous sheet of absorber on a crystalline support, the absorbing metal film was deposited on a one-micrometer thick silicon nitride membrane that was lithographed to resemble the web of an orb spider. In a spider web the fly is caught, while the wind blows through. In the Spider Web bolometer, the millimeter waves are absorbed and the cosmic rays pass through. After careful optimization, these spider web bolometers with Ge thermometers were used in BOOMERANG, MAXIMA and nearly all CMB experiments for the next decade, including the European Space Agency Planck mission. Sensitivities limited only by the fluctuation in the rate of the arrival of photons were achieved.

Lange soon moved to Caltech, taking the South Pole project with him and the two balloon groups, Berkeley and Caltech, became "friendly" competitors. MAXIMA first flew in 1998 and soon returned a spectacular 10×10 degmap of the CMB anisotropy [51]. BOOMERANG also had flown by this time and the two competing groups were to publish almost simultaneously. The unifying theme however was that the data from both experiments agreed extremely well, showing that possible systematic errors were under control. When combined, the data gave strong evidence that the theory of the evolved anisotropies was correct. The theoretical fit showed that the universe is flat (no overall curvature) and that the mass-energy density is $\sim$70% dark energy, 25% dark matter and only 5% baryons. The NASA WMAP space mission released data starting several years later, which agreed with all of these conclusions and provided the accurate data set that is the foundation of modern cosmology. The MAXIMA data [51], [52] ended up as the second and third most cited references from the Richards group.

Now that the CMB balloon anisotropy measurements had been superseded by WMAP, the next challenge was to use the CMB near 150 GHz to study clusters of galaxies. The hot electron plasma trapped by gravity in these huge clusters scatters the CMB and creates a dark spot on the sky with a diameter of $\sim 1\ \mathrm{min}^{-1}$. These experiments used 10-m class telescopes located at very dry sites. The high mapping speed required could only be achieved with large format arrays of bolometers. When he was a postdoc on MAXIMA in the Richards group, now Berkeley Professor Adrian Lee started development of a whole new class of superconducting transition edge bolometers employing negative feedback [53], [54]. These bolometric transition edge sensors (TES) could be fabricated into large format arrays entirely by thin film deposition and optical lithography, without the hand assembly characteristic of composite bolometers using Ge thermometers. They are low impedance devices, which reduce problems with microphonic noise. They use a cold superconducting quantum interference device (SQUID) readout amplifier, which has sufficient noise margin to permit multiplexing the output of many bolometers in a single amplifier, so as to reduce the number of leads to the cold stage.

At this point, Richards retired as group leader and Lee, along with Berkeley professor Bill Holzapfel oversaw the construction of a 330 element TES bolometer array camera (APEX-SZ) for the APEX telescope in the high Atacama desert of Chile, and a 960 pixel array camera for the South pole Telescope [55] in 2009. Both arrays use horn-coupled TES bolometers with spider web absorbers. The detector outputs are multiplexed using a frequency domain SQUID output multiplexer developed at Berkeley [56]–[58]. Data on clusters of galaxies are now being published from both of these projects.

A major present thrust of the Lee–Holzapfel–Richards group is to measure the anisotropy in the polarization of the CMB. Theory predicts that extremely accurate measurements of very tiny polarizations will yield far earlier information about the universe than is now available. The experimental concept of using polarization sensitive bolometers and a rotating half-wave plate polarization modulator was tested in a balloon flight called MAXIPOL [59], [60], which used MAXIMA hardware.

Professor Lee is currently leading a large team on a new experiment called Polarbear [61], which will use a specially designed 3.5 meter telescope now being assembled in Chile. The receiver for Polarbear is under test. It contains 1350 multiplexed TES bolometers, operated at 250 mK. The focal plane is packed with hemispherical lenselets, each of which feeds a crossed double slot antenna for receiving the two orthogonal polarizations. The antenna outputs pass through four lithographed superconducting microstrip band pass filters into two matched loads with TES thermometers, one for each polarization. A follow-on implementation uses a broad band sinuous line antenna with a novel frequency multiplexing filter that has been demonstrated with up to seven contiguous bands. The plan is to add two more complete telescopes to the project.

Polarbear will try to measure gravitational waves (large angular scale) and gravitational lensing (small angular scale) through the CMB polarization anisotropy. It is a grand project for a grand goal, and a very fitting use for the transition edge sensor that will help us spectrally image the edge of the universe. I cannot help but admire the many forward steps from the boy tinkering in the basement of his father's house in Riverside, CA to the man who is helping to unravel the mysteries of the universe.

As we finished our interview, Professor Richards, beaming with pride, showed me his home laboratory where he spends time, not inventing detectors for recording infrared photons, but improving his skills as a wine maker. As a vertically integrated vintner, he enjoys growing and tending the grapes, making the wine, with complete control of the process. It is perhaps a fitting way of coping with a profession that often demands large scale ventures, interfacing with many dozens of individuals, frequent compromises and limited control over the outcome of your work.

As a young student at Harvard, Paul Richards was exposed not only to mathematics and physics, which he found matched his innate talents very nicely, but he was expected to take classes in humanities, art and literature, and dare I say, even to appreciate these fields of study. This diversity serves him well and it is apparent in the way he interacts with people, the style in which he lives, and in the items he chooses to surround himself with in his daily life. His wife of many years, Audrey Richards, points out that Paul has "failed retirement." For his willingness to take on the big challenges and the tenaciousness to see them through, we are all glad that he has.

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