Terahertz Pioneers

A Series of Interviews With Significant Contributors to Terahertz Science and Technology

THIS MARKS THE SIXTH in our continuing series of interviews with **Terahertz Pioneers**: individuals who have, over many years, contributed significantly to terahertz science and technology. The Editor-in-Chief, with the support of the IEEE MTT Publications Committee, has chosen to incorporate these biographical sketches within our more formal technical journal, because of the diversity of disciplines that make up the THz community and the prior absence of a single unifying publication with sufficient outreach to extend across the whole of the RF and optical THz disciplines.

These short vignette pieces, highlighting senior members of the terahertz community, are intended to serve as a guide and inspiration for those who are just beginning their professional association with this field of study. The articles take the form of personal histories, but with a technical bent, so that the reader can get a short introduction to the topics presented. Extensive references are included for those who want to delve more deeply into historic or scientific detail. In addition, to go beyond a strict technical review, and to take better advantage of the information and commentary only available through a direct discussion, these vignettes take on the less formal style of an oral reminiscence rather than the more formal style of a research article. The Editor-in-Chief has taken some leeway in this regard, for the benefit of communicating more fully the character, experiences, and historic circumstances that have shaped our community and set the directions for our collective research.

As a means of further assuring that the true flavor and circumstances of the contributions detailed in the text come through to the reader, all of the articles are compiled after a face-to-face interview. The final text is shared with, and often helped considerably by, comments from the subject of the article. The Editor-in-Chief hopes you will enjoy the short diversion of reading these articles as much as he, himself, enjoys the process of composing them.

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As with the premier article in this series, it is appropriate that we highlight an area of THz technology that has dramatically expanded its scope, direction and applications—terahertz (THz) photonics. Although there have been several individuals who have fundamentally contributed to terahertz generation and detection using CW and fast-pulsed optical laser techniques, no one has been as staunch a supporter and as stalwart a contributor to these methods as Professor Daniel Grischkowsky. After 15 years of devoted service as an IBM Watson senior scientist and section manager, he was informed that the company would no longer support his THz time-domain investigations. Rather than give up on this research area that he had so patiently sowed and that was just beginning to bear fruit, he chose to leave the organization. This decision proved to be a good one for the terahertz community. Through his appointment at Oklahoma State University, Stillwater, Professor Grischkowsky has continued to develop new THz concepts and applications and has indeed begun to reap the harvest that he has been cultivating since he began his THz investigations more than 25 years ago. Professor Grischkowsky is a true THz pioneer and a role model for those who choose the oftentimes difficult path of placing scientific integrity and passion above corporate interests.

Daniel Richard Grischkowsky and I sat down together for a wonderfully personal and enjoyable conversation at his office at Oklahoma State University on April 6th, 2012. The following article is based on the contents of that discussion.

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Daniel Richard Grischkowsky embraces Stillwater, OK, USA, as his home. In between teaching in the U.S., and now also in China, he very much enjoys his research activities in THz generation, propagation and detection. He is hopeful for significant applications that will support his long-term involvement in this frequency regime, and is focusing on THz communications. We sat down together for a wonderfully personal and enjoyable conversation at his office at Oklahoma State University on April 6th, 2012.

Terahertz Pioneer: Daniel R. Grischkowsky

"We Search for Truth and Beauty"

Peter H. Siegel, *Fellow, IEEE*

ALWAYS a bit of an independent, and the first of his family from rural Oregon to attend university, Daniel Richard Grischkowsky's[1] early interests in rebuilding automobile engines turned to civil engineering, then engineering physics, and finally came to rest in experimental physics at Oregon State University, Corvallis, USA. After a short time in the OSU Corvallis graduate program, Dan set his sights on the east coast. Despite leaving many disheartened faculty members behind, who entreated him to stay on; he enrolled at Columbia University, New York City, in 1963. Columbia physics was a vibrant place in the 1960's with many notables on staff that served as role models for those incoming students that made it past the entrance exams. Grischkowsky was completely sold on his decision when, during his incoming interview in the summer of 1963, Professors Polykarp Kusch (shared the 1955 Nobel Laureate in Physics with William Lamb for determining the magnetic dipole moment of the electron and one of the fathers of quantum electrodynamics), and Henry Foley (noted EM theorist who worked with Kusch on his prize winning research), allowed him to pass the doctoral program language requirements on the spot, by having him stumble through a couple of pages of German (Kusch) and Russian (Foley).

Coming from a smaller school, Grischkowsky had some academic catching up to do at Columbia, and after successfully negotiating his classes, ended up working with Sven Hartmann (now Professor Emeritus) on electron spin echo [1] in ruby crystals. Grischkowsky worked on explaining this non-equilibrium process, that involves optical stimulation and inhomogeneous relaxation of magnetically confined spin systems, and he showed why spin echo was strongly correlated with field alignment [2], [3].

This was the era following the birth of the maser and laser, and with Charles Townes' historic work at Columbia still fresh (maser/laser inventor/pioneer and 1964 Nobel Laureate in Physics), it was natural that Grischkowsky spent time working on electronic processes and material systems that were popular at the Columbia Radiation Lab.

DANIEL R. GRISCHKOWSKY

In seeking out techniques that differed from the continuous wave experiments many of his colleagues were performing, Grischkowsky took a lesson from Theodore Maiman's pioneering work on optical masers (Maiman is the inventor of the pulsed ruby laser—the first operational laser—in 1960 at Hughes Research Lab, Malibu, CA), and he began to zero in on the pulsed techniques that would later serve him so well. He recalls that the environment at Columbia was extraordinarily stimulating, and that the teaching method focused more on lab experience than class work. Experimentally inclined students were encouraged not only to spend lots of time operating and improving instruments in the lab, but also to use the metal, glass and electronics shops, and to design and build their own apparatus. Despite the emphasis on building your own equipment, Grischkowsky revealed one piece of very useful advice he had at this time from Columbia colleague and Hartmann post-doc, Isaac Abella (former Townes student and later Professor of Physics at the University of Chicago, Illinois, USA). When Abella noticed Grischkowsky spending lots of time fixing and upgrading lab instrumentation, as many experimentalists have the tendency to do, he urged him to "*use what you have*" and don't waste time tweaking the instrumentation so that it works just a little better. This advice, along with the educational values at Columbia—which emphasized conceptual understanding rather than simply equation solving—are cornerstones that Professor Grischkowsky embraced, and which form the basis of much of *his own advice* to young students.

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When he graduated in 1968, and started to look around for permanent positions, Grischkowsky purposely decided to stay away from pure academics. Instead, he hoped to pursue full time research at one of the premier industrial solid-state physics laboratories that comprised the backbone of applied science in the US at the time. He was offered a permanent position at the IBM Thomas J. Watson Research Center, Yorktown Heights, NY, with the mantra *"Make the Future Happen."*

Grischkowsky entered the Physical Science department at IBM that included about 100 other research staff members. He circumspectly related that, although everyone had adequate resources and freedom, the whole staff was rigorously evaluated and ranked 1-to-100, and it was not uncommon for individuals to be shifted over to activities that were less free of direct corporate interests. He later had a very personal encounter with this system when he served as a staff liaison to the IBM corporate research director's office. In this role he was responsible for collecting, sorting, verifying and reporting the scientific accomplishments and personal merits of the scientific staff at IBM Yorktown; Zurich, Switzerland; and Almaden, San Jose, CA. This experience later had some influence in his choice of a lab motto at Oklahoma State (at least the first search term), *"We search for truth and beauty."*

At IBM Watson, Grischkowsky took up work on adiabatic processes involving pulsed fields. He observed self focusing [4] and defocusing [5] of vapor using strong magnetic fields, and began examining crystal resonances with an eye towards furthering the understanding of laser systems. These studies led him to develop the *adiabatic following model* [6] in alkali vapours, in which the dipole moments of the atoms remain aligned with the imposed laser pulse field as it propagates through the gas. This model explained the focusing and defocusing, as well as pulse steepening [7] and group velocity slowing [8]. Close lab colleagues and mentors at this time included John Armstrong (now retired IBM vice-president for science and technology), Gerald Burns (died 1991, known for the first demonstrated semiconductor injection lasers and glassy ferroelectrics), and Peter Sorokin (co-inventor of the dye laser, now a retired IBM Fellow).

In the early 1970's, Grischkowsky began working with dye lasers, and his interests in propagation studies steered him towards optical fibers, which were then in a fairly early stage of development. IBM emphasized working on *"research that mattered"* and encouraged their staff to jump into new areas as soon as they started to show merit. Taking advantage of his strong background in pulse excitation, Grischkowsky started examining picosecond pulse propagation in single mode fibers and soon showed that the inevitable pulse broadening was reversible [9], [10]! He demonstrated a reversely dispersive delay line using a sodium vapor cell, and was able to reassemble dye laser pulses that had been broadened by passage through optical fiber [11], [12]. Soon afterwards the technique was implemented directly in fiber by making use of nonlinear birefringence [13].

This patented optical-fiber pulse compressor technique was the basis for many useful applications, including frequency swept pulses that could be later recompressed, resulting in a form of optically chirped radar [14]. It allowed Grischkowsky and his IBM colleagues to achieve the then world record for the shortest continuous optical pulse sequence—12 fs, 500 Hz repetition rate [15]. The pulse manipulation technique resulted in the R. W. Wood prize for Grischkowsky in 1989 and was eventually commercialized by Spectra Physics (Santa Clara, CA).

In 1986, Grischkowsky began working on what was to result in his most important contribution to THz science, optical pulse excitation of semiconductors. Mark Ketchen (currently a research director at IBM Watson working on quantum computing) was an expert on silicon, and suggested some experiments using simple lithographic transmission lines. Both had heard about David Auston's experiments at Bell Laboratories[2] on optically excited pulse propagation in electro-optic crystals [16] and their free space radiation via dipole antennas on semiconductor surfaces [17]. Repeating parts of Auston's experiments with a commercial undoped silicon-on-sapphire wafer did the trick. The IBM team was able to launch and detect sub picosecond electrical pulses propagating on a coplanar waveguide transmission line [18]. The electrical (THz) pulses were generated by exciting the region between two of the three coplanar strips with an 80 fs dye laser pulse. The optical pulse generates carriers that short the transmission line and launch a propagating waveform. The waveform was sampled up to 8 mm down the line using a photoconductive gap driven by a time delayed portion of the optical excitation pulse. Sweeping over the delay, the resulting temporal interferogram mapped out the sampled pulse, which was broadened from 1.05 to approximately 2.6 ps [18]. Also, the on-wafer electrical pulses were much narrower than models predicted and the propagation loss was very high (nearly 40% in only 8 mm).

Since the observed pulse broadening and loss were almost an order of magnitude greater than the prevailing IBM "gold standard" on-chip analysis code predicted, and this code was touted as including "all physical phenomenon known to God and man," Grischkowsky's initial experiments were considered suspect by his IBM colleagues. As it turned out however, the "gold standard" code did not include the *Cerenkov effect*. Grischkowsky soon realized that for the electric pulse, the coplanar waveguide was acting like a perfectly matched leaky wave line, and generating shock waves that radiated into the substrate. Hence the on-chip pulse observations were quantitatively explained in [19] by the *Cerenkov Effect*, whose strength increases as the frequency cubed. A similar phenomenon was noted in electro-optic crystals by David Auston, a few years earlier [20].

In order to overcome the pulse degradation that was incurred on the transmission line, various colleagues suggested trying to examine the radiation being generated, directly at the site of the optical pulse. It was at this point that post-doc Christof Fattinger (currently at Hoffmann-La Roche Ltd., Basel, Switzerland) arrived from the Swiss Federal Institute of Technology, Zurich. Drawing from the recent theoretical work of Lukosz [21] who calculated that a dipole on a high dielectric constant substrate will radiate into the substrate with a fairly narrow beam; Fattinger and Grischkowsky [22] added a 9.5 mm diameter gold coated hemispherical sapphire lens (fully reflective mirror) to the rear of a small integrated dipole antenna fabricated on the silicon-on-sapphire wafer. Shifting the dipole slightly off-axis from the hemisphere, they then illuminated the

[2]See THz Pioneer article in the inaugural issue of this TRANSACTIONS, vol. 1, no. 1, September 2011.

antenna from the air side with their pulsed optical source and measured the reflected electrical energy (THz signal). This energy was now being propagated through the sapphire lens, reflected off the spherical surface, and then refocused back onto the silicon-on-sapphire wafer, but on the opposite side of the spheroidal focal point (see Fig. 1 in [22]). To Grischkowsky's delight, the sampled THz signal at the output focal point was huge: about half the amplitude of the THz signal they had generated at the site of their transmission line coupled pulse, and 10% of the signal from the lens coupled dipole itself.

This dipole generated, substrate coupled, THz signal was to change Grischkowsky's professional life! Using techniques that had been pioneered by Caltech Professor David Rutledge [23], [57], Fattinger and Grischkowsky next removed the gold coating from the hemispherical sapphire substrate lens, added a completely separate lens and dipole for use as a receiver, and were then able to generate, focus, propagate (through free space), collect, refocus and detect THz pulses with very high efficiency [24].

In an even more dramatic breakthrough, Fattinger came back from the lab one day in 1988 with a measurement that was very puzzling. After propagating about a meter, the received THz pulse contained several low amplitude ripples that were not present on the launched signal. No matter what Fattinger tried electrically, he could not get rid of these ripples. Grischkowsky recalled that in his Columbia days he had heard microwave engineers complain about a similar problem when they tried to propagate radar pulses through the atmosphere near 22 GHz (the infamous microwave water absorption line peak). In a true leap of faith, he told Fattinger that it must be water vapor absorption impacting the THz signal transmission! Fattinger immediately went back to the lab, borrowed a large plastic trash bag from the local janitor, used it to fully enclose the THz beam path, and then filled the bag with helium gas. Sure enough the ripples immediately disappeared. They just as quickly reappeared when a damp sponge was added to the bag. Grischkowsky and Fattinger had just demonstrated a very simple and elegant broadband free space THz *time-domain spectrometer* (THz-TDS) [25]! When post-doctorate Martin van Exter arrived later that year, they were able to generate the first detailed THz-TDS spectrum of water vapor [26].

These experiments opened the door to an extremely wide range of THz measurement which kept Grischkowsky and a slew of post-docs very busy, and very happy, over the next several years (e.g., 27–33). Grischkowsky recalls fondly, that at this time, everything always worked much better than he had anticipated—a true rarity in most scientific careers!

Then in 1992 things at IBM began to change. The company underwent a major restructuring, and management was pushing Grischkowsky to redirect his research. At one point, after several rounds of repeated re-organizations and the inexorable time and efficiency drains, Grischkowsky piped up at an all-hands meeting with the poignant question to IBM management, "Have you finally got the restructuring to the point at which you are happy with it, so we don't have to keep going through these very debilitating changes." He recalls his question received a standing ovation from the audience, but did little to affect the company's behavior. At the same time IBM management was very friendly to universities. They had no problem agreeing to Grischkowsky's request, when in 1993 he asked his management if he could move his entire lab to the Oklahoma State University, Stillwater, where he had been recruited to a chaired faculty appointment by then physics Professor Richard C. Powell (now Professor Emeritus at University of Arizona, Tucson).

Shortly afterwards, Grischkowsky pulled a large truck up to the IBM Thomas J. Watson Research Center loading dock and proceeded to pack up everything he could legitimately move to Stillwater, and then some. Three months later his lab at Oklahoma State was fully set up and operational, and he was back in the THz science business!

At Oklahoma State, Grischkowsky continued his varied THz time-domain spectroscopy experiments with students and post-docs [34]–[36], including an interesting application on the spectroscopy of flames [37]. He also began working on THz ranging [38] and THz wave propagation in various media, amongst other projects. He and his students and colleagues, notably R. Alan Cheville (now a Professor at OSU and program director at the National Science Foundation), published more than 25 journal articles and many dozens of conference papers between his arrival at OSU in 1993 and the start of the new millennium. A few topics that have been overlooked, but are worth reading are his papers with Matt Reiten (now at Los Alamos National Laboratory, New Mexico, USA) on THz ranging and optical tunneling [39], [40].

In 1999, Grischkowsky started publishing his first papers on THz waveguides specifically characterized for pulse propagation [41]–[44]. He and his students continued to examine various hollow core and solid guide dielectric and metallic structures, as they searched for a solution to the loss and dispersion issues that plagued THz TDS systems when they did not operate in free space [45]–[48]. By 2005, they had zeroed in on a common class of microwave low dispersion waveguides—parallel plates. They first experimented with photonic band gap type structures [49] but later shifted to the more classic metal plate waveguides [50]. This low dispersion guide medium allowed Grischkowsky to make very sensitive spectroscopic measurements on thin films, including liquids and powders, using the differential absorption properties, and extended interaction lengths of coated metal surfaces [e.g., [51]–[54]].

Most recently, Grischkowsky and his students at OSU, have been pursuing THz pulse propagation in the atmosphere, with an eye towards making an impact on ultra wide-band communications [55], [56]. While I was visiting, he proudly showed me what must be the longest *indoor* humidity controlled THz atmospheric transmission test range in the world today-167 meters! With this new measurement capability, which is consistent with his mantra of taking a new instrument and using it in a new way; and with his continuous pursuit of new ideas that have significant impact, Dan Grischkowsky will certainly accomplish one of the major goals of his long and fruitful career: *to realize the full potential of THz science and technology*. Many of us are counting on it!

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