Terahertz Pioneers

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

AS A TRIBUTE to individuals who have contributed significantly, and over many years, to the Terahertz community, and as a guide and inspiration for those who are just beginning their professional association with this field of study, these transactions have included, on a regular basis, a series of biographical interviews with technical researchers who have appreciably impacted the THz community in a positive manner. In order to go beyond a strict technical review and to take better advantage of the information and commentary only available through a direct discussion, these articles take on a less formal style than the research articles that can be found within the remaining pages of the transactions. 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 further means of assuring that the true flavor and circumstances of the contributions are expressed in the text, 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, with the support of the IEEE MTT Publications Committee, has chosen to incorporate these biographical articles within the 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. The Editor-in-Chief hopes you will enjoy the short diversion of reading these articles as much as he himself enjoys the process of writing them.

Every so often one must take a good look at the rules that have been set up for any enterprise. I have always felt it is a good idea to stretch them, or even to break them on occasions of particular merit. This is especially so in science, where innovation often can only come when the established truths or methods are overturned, or at least side-stepped—the overused "working outside the box" analogy. This is one of those times. For the past four years these articles have preselected candidates whose careers were at their twilight—or at least one can say that the candidates were all beyond their mid-sixties in age. However, we cannot complete the comprehensive set of THz Pioneers without including an individual who is only 59. Professor Xi-Cheng Zhang[1] is known to practically everyone in the THz community, from the moment they pick up an article or look up a reference with the term "THz" in the text.

With over 350 peer reviewed articles, 250 conference publications, 400 colloquia presentations, 23 books and book chapters, and 29 patents, *98% of which are all on THz science, technology and applications*, Xi-Cheng is almost certainly the most prolific writer and speaker in our niche community. This is not the only reason he is so well known to us, and so well regarded amongst us, however. In addition to all the time he spends on his own technical and administrative tasks, he has also circumnavigated the globe the equivalent of more than 120 times, amassing 2.5 million airline miles since 1990 on visits to colleagues, conferences and individually arranged speaking engagements. There are few THz researchers who have not met Professor Zhang personally, and none I have ever encountered who did not voice an enthusiastic endorsement of him individually.

In addition to his exhaustive list of professional and volunteer activities, Xi-Cheng has also been caught up in the public's occasional interest in the THz field and its touted applications. As those of you who have had similar experiences understand, this is not always a positive encounter. However, Professor Zhang has not been shy about sharing his achievements with the press when asked, and he and his students and staff have been part of so many newspaper, magazine, radio and TV reports, I think we can formally recognize him as the public "Face of THz."

On a more personal note, perhaps few of you know how much Professor Zhang needed to overcome in order to get to the position of respect he now holds. Even fewer may appreciate how much his personal attitude towards life, and especially his ability to focus all his energy on a task at hand—even if it is of value only to others, has influenced his career path. This is a very special *THz Pioneer* indeed, and one whom I have grown to admire more and more, as I find out more and more about his human accomplishments, as well as his technical ones. I hope Xi-Cheng Zhang's unique life experiences, and their influences on his very successful career, come through in the story you are about to read.

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[1]I met with Professor Xi-Cheng Zhang at his office at the University of Rochester, Institute of Optics, Rochester, NY, USA on the morning of June 23rd. It was a wonderful sunny and warm day in a city not known for its good weather. Perhaps that accounts for the wonderfully open and upbeat conversation we squeezed between pre-arranged trips, and before a stack of meetings that Professor Zhang had to attend both in the middle of, and following our interview.

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Terahertz Pioneer: Xi-Cheng Zhang

"The Face of THz"

Peter H. Siegel, *Fellow, IEEE*

XI-CHENG ZHANG[1] is one of those incredibly positive individuals who defy statistics, and rise above the circumstances that they were dealt at birth.[2] Born in Beijing, China, in 1956, Xi-Cheng was the son of Fan Zhang, a Deputy Chairman and Editor-in-Chief at the China News Agency, and Jiu Chen, an eye doctor. He has one brother and two sisters who now reside in the United States.

As the son of professional parents, the Cultural Revolution was a particularly disruptive time for Xi-Cheng, who in 1966, while still in the 3rd grade, was given one week's notice to leave his family and board a train for Jiangxi province, 1500 km to the south of Beijing. He remembers his sister rushing to the train station to catch him before his departure, lest he leave without even having a blanket to sleep with. He (as well as his siblings and his father) would spend the next 3 years on a rural farm, together with many other relocated children, while his mother remained in Beijing. Perhaps as a consequence of this experience, Xi-Cheng learned to love animals, and as a child, recalls wanting to become a zoo keeper (*luckily he chose THz instead—although this explains our frequent discussions about my beagles, Darwin and Maxwell—bio and RF, for those who know me!*).

After 3 years, Xi-Cheng was reunited with his mother in Beijing, where he was able to return to school. His father remained in the countryside for another year. Having graduated high school, Xi-Cheng was sent to a suburban farm, Huang Hua Cheng (Yellow Flower City) in Huairou county, outside of Beijing City and not far from an expanse of the Great Wall of China. He was appointed as a Brigade team leader,[3] and along with a group of three other high-school students, and four pre-high school students, he was to help this particularly impoverished village. Xi-Cheng recalls that the village was so poor that food, as well as clothing were insufficient to sustain the population. Huang Hua Cheng was close to a large reservoir however, and his team's major project was to construct a hydropower station. There was no shortage of labor, but there was no money to buy materials, and no one had the slightest idea of how to construct a suitable tower and sluice, let alone the hydroelectric generator to produce useful energy.

XI-CHENG ZHANG

Xi-Cheng combed accessible libraries for the necessary texts and taught himself how to layout and reinforce concrete structures and calculate loads. In order to raise money for procuring materials and a working generator, he went from office to office within the county government. As poor as it was, he managed to accumulate donations by focusing on family self-interest, rather than communal beneficence. He asked parents to consider the alternatives, and the positive impact the new project might have on the lives of their own children. Two years later, he had his hydro plant and was bringing in a small income to the village by selling excess electricity to neighboring communities! He was even able to stock the reservoir with fish—which he trucked in from a nearby hatchery, thus providing a much appreciated and steady source of food for all.

Xi-Cheng's very creative and successful time as a Brigade team leader, combined with his long term residency in rural

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[2]See for example the extremely interesting account of success based on circumstances, by Malcolm Gladwell, "Outliers: The Story of Success," Little, Brown and Company, NY, NY, c. 2008.

[3]Approximately 670,000 brigades and 5 million teams were organized in the 1970s to work at the grass roots level to oversee and re-educate, but also to help improve life in rural communities throughout China (Tyrene White, "*China's Longest Campaign: Birth Planning in the People's Republic, 1949–2005*," Cornell University Press, NY, c. 2006).

China, led him to believe that he would remain in the countryside for his entire life. A "fortuitous" calamity in early 1977 was to change all this. One of the valves on the hydro plant reservoir had became clogged, and Xi-Cheng volunteered to make an impromptu and ill equipped scuba dive to try and free the mechanism. In the process he seriously injured his hands, which became infected and eventually gangrenous. He was transferred to a hospital in Beijing where he was to spend the next several months recovering, and fortunately only a small scar on the wrist remains as a reminder of this near catastrophe.

While recuperating, Xi-Cheng read voraciously. Mao Tse-tung had passed away in 1976, and as a consequence the Cultural Revolution was at an end. Traditional university education was being reestablished. The national college entrance exam (NCEE or *Gaokao*) that had been suspended under Mao, was re-instated by Deng Xaoping in 1977. Xi-Cheng's father—now finally back in Beijing—and realizing the academic capabilities of his children, recommended that Xi-Cheng use his recovery time to study, and to sit for the exam. It was a two-day ordeal covering math/physics, Chinese and politics. Individuals aged 15–36 were eligible. Xi-Cheng scored #1 out of all the participants in his county! The high score landed him in Peking University in the prestigious Class 77 (approximately 5.7 million people took the examination that year and only 4.8% were admitted to university, the lowest percentage in the history of the Peoples Republic of China[4]).

It took about a year before the university facilities were actually ready to admit all the students, but in 1978 the gates were opened and Xi-Cheng entered along with an exceptionally talented group of attendees. As one might guess, all worked extremely hard and all were very self-motivated. Xi-Cheng was very interested in math and science and spent almost all his time studying. He did manage to meet his future wife, Wenling (Wendy) Yan, a distant cousin, and daughter of the Provost at Peking University—an engagement that brought him to this high office perhaps more times than he might otherwise have desired!

In 1981, Nobel Laureate, Tsung-Dao Lee (Columbia University Physics Department) started up a pioneering scholarship program to bring talented Chinese students to the United States for doctoral training. Through Lee's CUSPEA (Chinese United States Physics Examination and Application) program[5], 100 students who passed an exam and an intensive personal interview were given an opportunity to apply to any one of 63 (later 97) U.S. universities that were part of the arranged scholarship program. In August 1981, Xi-Cheng received two suits, $400 cash, and an airline ticket to the United States. He did not even have an undergraduate degree in hand as yet (the official document would come later), but he boarded a plane for Brown University, Providence, RI, USA, one of the schools he applied to partly because Providence translated into Chinese as "*a heavenly place*." Wendy, in turn (but not as part of the CUSPEA program), went to Vancouver, Canada, that same year to attend Simon Fraser University where she studied business.

At Brown, Xi-Cheng recalls sharing an apartment that gobbled up almost half his stipend, but U.S. inflation in the early 1980's helped enormously in a rent stabilized dwelling, and he soon was earning enough to be comfortable. Not surprisingly, he chose to work in physics because of T. D. Lee's influence. Like himself, Zhang sought out a faculty adviser who was young and ambitious, and he collaborated with Arto Nurmikko, who was then working in the Electrical Engineering department. Nurmikko was working on semi-magnetic semiconductors, and in particular, on picosecond lasers and ultrafast phenomena in semiconductor super-lattices (Nurmikko still runs a large bio-science research group at the university). During his thesis work, Zhang and Nurmikko published a substantial number of journal and conference papers on exciton (electron-hole pair formed from photon absorption) behavior in semiconductors exposed to optical pulses [1]–[10]. Xi-Cheng married Wendy in 1982, and graduated with a Ph.D. degree in physics from Brown in 1985 (degree awarded in 1986).

Following a short research posting at MIT in the latter year of his dissertation, *Dr.* Zhang weighed the offer of an MIT post-doc ($23,000/year) against a training appointment at Amoco Research Laboratory, Naperville, IL ($40,000/year). While still on a U.S. J-1 visa (which allowed 2 years of post-graduate training, but then required a mandatory return to the visa holder's home country), and with a son in tow, Xi-Cheng chose the more lucrative Amoco offer. He spent two years in Naperville working on electro-optic sampling [11]–[13] with Ravinder K. Jain (now at University of New Mexico, Albuquerque, NM, USA), where he recalls lots of company projects and lots of paperwork!

From Amoco, Zhang expected he would go back to China at the end of 1987, when his visa expired—13 boxes had already been shipped to Beijing. The plan was to take an Associate Professor offer at Peking University brokered by noted physicist Yuen-Ron Shen (UC Berkeley emeritus) who was recruiting Chinese ex-patriots to serve in PRC universities. However, there was also an invitation pending to go to Imperial College in London, U.K. for a six month visit, and Peking was refusing to allow the travel. Zhang realized that the position in Beijing would be much more restrictive than he had anticipated. At the same time, Wen I. Wang, who had known Xi-Cheng during his time at Brown University, offered him a short post-doc at Columbia University (NY, USA) working on molecular beam epitaxy and optical spectroscopy, as well as a J-Visa waiver and conversion to permanent US residency. Zhang and his family moved to New York City in 1987 and took up residence in Columbia faculty housing on 125th street and Riverside Drive in New York city. This turned out to be a very prescient decision as David Auston [14] arrived at Columbia shortly afterwards, from AT&T Bell Laboratories.

Auston was transferring his pioneering work at Bell on subpicosecond pulse excitation of crystals to produce radiating RF fields [15]–[17], to the university. For Xi-Cheng, the research was both new and exciting, as well as a perfect fit for Zhang's own background on high speed photonics, acquired at both Brown and Amoco. With Wang's blessing, Xi-Cheng

[4]en.wikipedia.org/wiki/National_Higher_Education_Entrance_Examination. An acclaimed film about the 1977 Gaokao was released in April 2009 by the Shanghai Film Group called "Examination 1977" starring Wang Xuebin.

[5]CUSPEA ji nian ce, CUSPEA Program Office, Beijing, Ke xue chu ban she, 1986. In Chinese.

joined Auston's research group in 1988 and soon became his "right hand"; purchasing equipment, setting up and running experiments, helping with proposals and program reporting, training and mentoring students, writing papers, and giving presentations.

The year, 1990, was the one in which the hard work and prior training really began to pay off. Although Auston had been able to effectively generate and propagate optically induced THz pulses in crystalline materials such as $LiTaO_3$, he had yet to come up with a way to efficiently radiate the RF into free space due to severe dielectric mismatch at the crystal-air interface. Along with a graduate student, Binbin Hu at Columbia, and P. R. Smith at Bell Laboratories, Zhang and Auston succeeded in developing a simple and effective method of radiating and collimating the THz energy. They coupled a hyper-hemispherical Sapphire lens to the output surface of the $LiTaO_3$ crystal [18]. At about the same time, the Columbia/Bell Labs team made another important breakthrough. They found that they could generate, and then steer the radiated THz pulses in a range of optically illuminated photoconductors by irradiating large open areas at non-normal incidence [19]–[23]. Since the RF signals were derived from large apertures, the resulting free space THz beams had much higher directivity than those generated from small dipole or other wavelength-scale antennas. The technique enabled the Columbia team to investigate a wide range of semiconductors, many of which were found to produce efficient THz beams [24]. This both expanded the available opto-electronic materials, and allowed for the possibility of tailored structures [25]–[27]. Arrays came next, for increased power [28]–[30]. After this, circuits and devices [31]–[35] as well as applications relevant to semiconductor physics and material characterization [36]–[39] were worked in. A nice review by Zhang and Auston came out in 1992 [40]. In a final highly cited project at Columbia, Lu, Zhang and Auston observed THz radiation from optically pumped bulk $LiNbO_3$ and $LiTaO_3$ using femtosecond [41], rather than picosecond pulses as in [42], opening up the door for higher frequency and higher efficiency opto-electronic RF generation.

At Columbia, Xi-Cheng's visibility increased enormously, and it did not hurt that he was traveling and giving talks at conferences and workshops at a dizzying rate—more than 50 in the three years he was working with Auston. As his network of professional colleagues expanded, it is no surprise that opportunities would come calling. After a colloquium at Rensselaer Polytechnic Institute (RPI) in Troy, NY, Physics Department Chair, Tim Hayes offered Xi-Cheng an associate professor position. Anxious for a chance to set up a lab of his own, and to build up a group of students that might continue his very successful foray into high frequency power generation and detection, as well as a strong feeling that raising three children (two boys and a girl) in New York City might not be the easiest thing to do, Xi-Cheng relocated to upstate NY in January of 1992. By this time, David Auston had moved on to more administrative functions at Columbia, where he was serving as Dean of Engineering. Despite the career shifts, the two colleagues have remained close friends to this day.

The start-up package at RPI was barely sufficient to purchase the basic lab instrumentation and the necessary optical gear to continue the pulsed THz generation and detection work. Xi-Cheng had to convince Coherent Inc., Santa Clara, CA, USA, to sell him the essential, but very expensive Ti-sapphire femtosecond optical laser and pump, on a three year time payment. However it did not take Zhang long to start accumulating grant funding. Within two years he already had received five NSF and two Air Force awards. By the time he would leave RPI some 20 years later, he had applied for and received over 200 grants totaling more than 35 million dollars!

The work at RPI started off slowly with some initial experiments on crystal interactions [43], [44], but ramped up quickly, with two highly cited papers on THz generation in a variety of new crystals [45], [46], including DAST [47] (dimethylamino 4-N-methyl stilbazolium tosylate [48]). Research expanded as new students and new grants arrived. A particularly interesting result showing that the THz radiation from optically pumped GaAs, and later zincblende (ZnS), could be enhanced and controlled by an applied magnetic field came out in 1994 [49]–[51]. There was also a series of experiments on THz generation from metal-semiconductor interfaces [52] that received significant attention. Much of this work is summarized in three book chapters [53]–[55] and several papers [56]–[58] from the period.

The real breakthrough however came in 1995, when graduate student Qi Wu and Xi-Cheng Zhang published their extremely influential paper on sensitive coherent THz detection using the AC Pockels[6] effect (rotation of the optical polarization in a crystal due to the presence of a time varying field) [59]. Directly quoting from the abstract of this paper: "In contrast to resonant photoconductive dipole antennas, free-space electro-optic sampling via the linear electro-optic effect (Pockels effect) offers a flat frequency response over an ultra-wide bandwidth and the potential for a simple cross-correlation signal of the terahertz and optical pulses." This ground-breaking paper was followed by several other well cited articles utilizing the new technique [60]–[63]. These include 2-D sampling in ZnTe with images captured on a CCD camera [64], coherent detection at 7 THz [65], and even mid-IR (37 THz) sensing and imaging [66]. Qi completed his dissertation in 1997 and is currently a research manager at nearby Corning Inc. in Corning, NY.

Throughout the late 1990s continued development and use of electro-optic sampling formed the basis for many dissertations, papers [67]–[70] and book chapters [71]–[73], and in particular a welcome comparison with direct antenna detectors [74]. In 1998, post-doc Zhiping Jiang and Zhang were able to perform the first electro-optic sampling measurements (THz generation and detection) on a chirped *single* optical pulse [75]–[78]. The variable frequency delays comprising the chirp (higher frequencies appearing at a different time stamp than lower frequencies within the pulse) provide the temporal variation in the optical interferogram normally derived by a slow moving mechanical delay stage. Jiang and Zhang went on to perform several imaging and spectroscopy experiments with the new technique [79]–[82]. Additional work during this period included THz imaging of tissues [83], optical waveguides [84], liquid

[6]The Pockels effect was discovered in 1893 by German physicist Freidrich Pockels at University of Heidelberg, who showed that an electric field can change the refractive index in birefringent materials with a linear dependence on field strength (en.wikipedia.org/wiki/Friedrich_Carl_Alwin_Pockels).

phase spectroscopy [85], and even THz imaging for currency identification [86]. In addition to the journal publications, Zhang and his RPI group presented more than 75 conference papers between 1997 and 1999 and Zhang himself gave more than 45 invited talks and colloquia.

Upon his return to RPI, after presenting one of the plenary talks at the 24th International Conference on Infrared and Millimeter Waves in Monterey, CA, USA, on Sep. 8, 1999 [87], an event that had put him under an unusual amount of stress due to a variety of logistics calamities, Xi-Cheng unexpectedly suffered a very serious stroke. For the second time, he found himself in the hospital with a life threatening ailment. He had lost a substantial amount of brain function and was paralyzed on his left side. His doctor told him he would likely remain in a wheel chair for the rest of his life. The university had thought his career over, and had placed him on long term disability. But Xi-Cheng was not your ordinary patient. He decided the people around him in the hospital were much worse off than he (*á la the villagers at the Great Wall*). He took on a positive attitude, and set to work on his rehabilitation. In a reasonably short time he had regained 85%–90% of his physical and mental faculties, and he went right back to work. The experience left him with a permanent loss of sensation in his extremities and some restrictions in head movement, but with a renewed appreciation of life. He confided that after his recovery, he paid more attention to his wife and family, worked even harder at helping others, and most importantly for our community, decided to stay in the THz field. The latter, because he felt he might no longer be able to muster the physical energy that it would take to start over in a new topic area!

If there was a gap in Xi-Cheng's career accomplishments after his stroke, or a drop in his energy level, or even a decrease in his manic international travel and speaking schedule, it is not apparent from his resume, or from *Web of Science*. The THz group at RPI was now involved in almost every area of science and application that encompassed or applied THz time domain techniques and instruments. Between 2000 and 2002, I counted 4 book chapters, 54 refereed articles, 49 conference publications, and more than 70 seminars and colloquia. Some of the most cited references from this period are reproduced in the bibliography [88]–[113], but they do not capture all the work that was accomplished, and there are many less cited THz papers that are of significant interest. A few of my personal favorites include extensive developments in THz tomography [105], compact THz instrumentation [89], some early carbon nanotube characterizations [103], and the most referenced of Zhang's papers [107] on opto-electronic materials.

In July 2002, RPI formed a new *Center for Terahertz Research* [114]. One and a half years later, in December 2003, University President Shirley Ann Jackson, presided over the inauguration of the more than 15 million dollars plus THz facility, containing a new million dollar laboratory endowed by the W. M. Keck Foundation [115]. Distinguished THz speakers at the event included Dan Grischkowsky [116], Yuen-Ron Shen (who first demonstrated optical rectification and generation of THz waves in crystals along with Paul Richards [117] at Berkeley, see [118, p. 409, footnote 5]), renowned solid-state device physicist, Michael Shur (a faculty member of the THz center), and of course the center director, X.-C. Zhang. The RPI *Center for Terahertz Research* quickly grew to more than 60 people, with 7 faculty members and more than 40 post-docs and visiting scholars, making it one of, if not *the largest* THz-exclusive research group in the world.

One of the projects that propelled the RPI center into the public eye [119], [120] was the demonstrated detection, using THz [121] and millimeter waves [122], of hidden voids and defects in space shuttle tiles after the *Columbia* accident that occurred in February 2003. Another popular, and continuing news story theme is the use of THz time domain systems for potential threat detection through imaging and spectroscopy, especially explosives [123] and bioagents [124]. The THz Center was part of a five year Multidisciplinary University Research Initiative (MURI) program from the US Army Research Office [125] and spent a lot of effort on this research topic. This trend, of keeping THz in the news, for better or for worse, was something that Xi-Cheng did not shy away from. Over the years Xi-Cheng has been interviewed by newspapers, magazines, radio and television program hosts, and science journalists. His research has appeared in more than 30 popular publications from Time Magazine to Popular Science. Professor Zhang, more than any other scientist, is the "public face of THz" as well as one of the field's most vocal advocates and spokespersons. This popularity certainly did not hurt the RPI THz center, which received more than $24 million dollars from 60 separate sponsors between 2002 and 2011, while Zhang was the Director!

All of the media attention in the early days of the THz center did not distract Xi-Cheng and his colleagues at RPI from their technical work, which if anything, expanded exponentially until there was almost no THz topic that could not be found in one of the THz center's papers. 175 journal papers, 100 conference publications and well over 150 presentations contain Zhang's signature between 2003 and 2011. Papers that received high numbers of citations include work on GaN HEMT sources [126], new opto-electronic source materials [127], millimeter-wave imaging [128], a time and frequency domain imaging comparison [129], FET detectors [130], tomographic imaging to detect structural defects [131], reflection spectroscopy of RDX [132] and other chemical threats [133], [134], laser induced plasmas for THz generation [135] and detection [136], [137] (more on this later), and a review on THz imaging and spectroscopy for defense applications [138].

Zomega Technology Corporation started out as a consulting enterprise for Xi-Cheng and his wife Wendy (CFO), in 1998, with funding garnered through various small business start-up grants that involved RPI as a partner. The name came from the street that Xi-Cheng and Wendy lived on near RPI—Omega Terrace, but Omega Corporation was already in use by another business. Wendy suggested that it might be trendy to add a letter in front (like the IOmega zip drive company, popular in the 1980s). ZOmega seemed like an appropriate choice for a multilingual family—Zee and Omega both serving as the last letters in their respective alphabets! After working with the DoD on various THz spectroscopy projects, Xi-Cheng realized there was a need for a compact commercial spectrometer, and decided to spin out the consulting company as a manufacturer, taking advantage of the many technical developments in his group at RPI. In

2005, Xi-Cheng, Wendy, and Wendy's MBA classmate, Thomas Tongue (CEO) incorporated Zomega Terahertz Corp., the first U.S. company to manufacture and distribute compact THz TDS (time domain spectrometer) instruments. Today Zomega produces and sells several very innovative THz spectrometers, as well as some broad band air-photonics based instruments. The company currently employs approximately 11 people and has more $2M in annual sales revenue.

Starting in 2005, Zhang, along with THz center Research Associate Professor Jianming Dai, and student Xu Xie, started working on the generation of broadband THz signals via optically generated plasma discharges in air. This was an interesting phenomenon that had been observed in the early 1990's by a group at UC Berkeley [139], [140], largely ignored, and then taken up almost ten years later in 2000, by a noted THz group in Germany [141] and at University of Pennsylvania [142]. Zhang immediately realized both the scientific and commercial application of the technique, both for generating THz waves at a significant distance from the observer, and for the ability to generate and efficiently radiate THz pulses with very broad frequency content, since there was no high index substrate to impede propagation or add undesirable absorption features. He and his RPI colleagues first expanded upon the generation mechanism, a four wave mixing process [143] and then characterized the THz fields [144]. Zhang and various collaborators have since significantly expanded both the methodologies for generating and detecting the pulsed plasma induced RF fields, as well as manipulating the direction, phase, bandwidth and strength of propagating THz pulses. A compact (table top) laboratory system was even developed through Zomega and is available as a commercial broad band fully enclosed THz spectrometer. Since its initial characterization and demonstration, many dozens of science and application papers have been published by Zhang and his students, only a few of which are listed here [135], [145]–[159]. The topic has become a field in and of itself, and has an extremely active following to this day [160].

From 2002 through to 2011, Xi-Cheng ran the RPI Center for Terahertz Research, as he continued to travel to, and collaborate with, almost every THz group in the world. He thinks the only major group he has yet to visit personally, is Dan Grischkowsky's at Oklahoma State! *In his continuing quest to seek out new THz colleagues and new THz groups* Xi-Cheng has given special emphasis to China. There he has advised or assisted in the establishment of THz groups at a large number of universities, often serving as an adjunct or visiting professor, to lend direct personal support. He makes on average 3 trips a year to China and is listed on 8 university faculties there. Combined with all his other visits around the world, Xi-Chang has logged more than 2.5 million air miles since 1990, swearing that only four of the flights (two separate vacations) involved trips that were not business related. For those of us who fly a lot in these times of very minimal travel comfort, it is a strong testament to Xi-Cheng's interest in his colleagues, and his personal sacrifice to continue to promote THz science and applications anywhere around the globe.

In 2011, an excellent opportunity came in from University of Rochester, NY, who were looking for someone to take over the directorship of their historic *Institute of Optics*. For Xi-Cheng, the decision to leave RPI after 20 years of continuous support—he had originally intended to stay at RPI only for a couple of years—was agonizingly difficult. However, after much tribulation, the chance to work with many of the best optics faculty and to make an administrative impact without giving up his technical goals, would win out. Xi-Cheng and his family moved to Rochester in January 2012, where he took up his current post as Director for The Institute of Optics. When he left RPI, Zhang took a lot of the instrumentation he had acquired over the years through his research grants, and the RPI *Center for THz Research* closed a year later. A few members of the staff did come to Rochester with him, but most of his students at RPI had already finished up, so the transition to his new post went very smoothly. Despite their desire to keep Xi-Cheng at RPI, and the administration's disappointment when he did ultimately leave the university, Zhang, as you might expect after getting a sense of his devotion to his colleagues, remains on good terms with his department, his former co-workers and the administration at RPI.

At Rochester, Xi-Cheng plunged into his work with his usual energy and positive approach. He immediately began implementing plans to build up the research and staff at The Institute of Optics, bringing in new students, revamping laboratories and classes, and setting standards and direction for the overall program. Although he has had less time for personal research, he is still actively engaged in many projects both at Rochester and in the dozens of THz laboratories around the world, where he collaborates. He has also taken on the role of Editor-in-Chief of *Optics Letters* and serves as Scientific Advisor and a member of the International Council for ITMO University in St. Petersburg, Russia. A comprehensive look at much of Xi-Cheng's technical work in the last couple of years is contained in a very extensive and thorough set of five review articles in a special issue set up just for him, by the Springer journal, *Frontiers in Optics* [161]. There you will find a full accounting of his most recent and continuing contributions to THz science and applications and a full list of recent references on almost all of his activities over the past five years.

It is difficult to close off an article on a person whose career is by no means at an end—this is the reason these articles have focused exclusively (until this particular piece) on individuals who have at least passed the age of 65. At 59, Xi-Cheng can still fit in an awful lot of new development in the active years he has ahead. However, we must close somehow, so perhaps an appropriate ending is to look back to the beginning, and attempt to seek an answer to Xi-Cheng's recipe for success. From all appearances, it seems that a passion for success permeated Xi-Cheng's entire life, even from his earliest days as a child, when he was abruptly pulled away from his home and family, and placed into what could only be viewed as exceptionally harsh conditions. Then, and later as a team leader, sent to a village of little hope, to perform a task without sufficient resources, he did not let the circumstances in which he found himself fill him with negativism towards those who pulled the strings. On the contrary, he chose to rise above the powers that desired to control his destiny, and to devote his energies to improving, whomever and whatever surrounded him. Making sig-

nificant strides within a competitive career in science and technology, given the external constraints that always surround one, requires a skill set that is perhaps not too different than the one needed to convince the inhabitants of a small rural village to put their own time and assets into a project that benefits the community as a whole. It is a skill we might all wish for.

Before parting, I asked Xi-Cheng if he had any advice to new graduate students. His response was simply, "Think about how you can outdo your advisor." ***Not very likely in this case!***

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REFERENCES

[1] X.-C. Zhang, M. Gal, and A. V. Nurmikko, "Free-exciton confinement by layer stacking-faults in GaAs: Evidence from time-resolved spectroscopy," *Physical Rev. B*, vol. 30, no. 10, pp. 6214–6216, 1984.

[2] Y. Hefetz, X.-C. Zhang, and A. V. Nurmikko, "Observation of exciton-exciton scattering in Cu_2O by time-resolved photomodulation spectroscopy," *Physical Rev. B*, vol. 31, no. 8, pp. 5371–5375, 1985.

[3] L. A. Kolodziejski, R. L. Gunshor, N. Otsuka, X. C. Zhang, S. K. Chang, and A. V. Nurmikko, "100, superlattices of CdTe–$Cd_{0.76}Mn_{0.24}$Te on (100) GaAs," *Appl. Phys. Lett.*, vol. 47, pp. 882–884, 1985.

[4] A. V. Nurmikko, X. C. Zhang, S. K. Chang, L. A. Kolodziejski, R. L. Gunshor, and S. Datta, "Excitons in CdTe/$Cd_{1-X}Mn_X$Te multiquantum wells," *J. Luminesc.*, vol. 34, pp. 89–97, 1985.

[5] X. C. Zhang, S. K. Chang, and A. V. Nurmikko, "Picosecond spectroscopy of excitonic localization in $Cd_{1-X}Mn_X$Te," *Proc. Soc. Photo-Opt. Instrum. Engineers*, vol. 533, pp. 101–105, 1985.

[6] X. C. Zhang, S. K. Chang, A. V. Nurmikko, L. A. Kolodziejski, R. L. Gunshor, and S. Datta, "Excitonic recombination at the CdTe/(Cd,Mn)Te heterointerface," *J. Vacuum Sci. Technol. B*, vol. 3, pp. 1300–1302, 1985.

[7] X. C. Zhang, S. K. Chang, A. V. Nurmikko, L. A. Kolodziejski, R. L. Gunshor, and S. Datta, "Time-resolved exciton recombination in CdTe/$Cd_{1-X}Mn_X$Te multiple quantum wells," *Appl. Phys. Lett.*, vol. 47, pp. 59–61, 1985.

[8] X.-C. Zhang *et al.*, "Influence of high magnetic-fields on exciton luminescence of $Cd_{1-X}Mn_X$Te multiquantum wells," *Solid State Commun.*, vol. 56, no. 3, pp. 255–259, 1985.

[9] X.-C. Zhang, S. K. Chang, A. V. Nurmikko, L. A. Koloziejski, R. L. Gunshor, and S. Datta, "Interface localization of excitons in CdTe/$Cd_{1/X}Mn_X$Te multiple quantum wells," *Physical Rev. B*, vol. 31, no. 6, pp. 4056–4059, 1985.

[10] X. C. Zhang *et al.*, "Excitons and their kinetics in CdTe/(Cd, Mn)Te and ZnSe/(Zn, Mn)Se quantum-wells," *Surface Sci.*, vol. 174, no. 1-3, pp. 292–298, 1986.

[11] X. C. Zhang and R. K. Jain, "Measurement of on-chip wave-forms and pulse-propagation in digital GaAs integrated-circuits by picosecond electrooptic sampling," *Electron. Lett.*, vol. 22, pp. 264–265, Feb. 1986.

[12] R. K. Jain and X.-C. Zhang, "New picosecond opt. Techniques for the control and measurement of high-speed GaAs ICs," in *1986 IEEE GaAs Symp.*, Orlando, Oct. 1986.

[13] X.-C. Zhang, R. K. Jain, and R. Hickling, "Electro-optic sampling analysis of timing patterns at critical internal nodes in gigabit GaAs multiplexers/demultiplexers," *Picosecond Electron. Optoelectron. II*, vol. 24, Springer Series in Electronics and Photon., p. 29, 1987.

[14] P. H. Siegel, "Terahertz pioneer: David H. Auston—Working collectively to combine complementary knowledge, perspectives and talents," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 1, pp. 5–8, Sep. 2011.

[15] D. H. Auston and M. C. Nuss, "Electrooptic generation and detection of femtosecond electrical transients," *IEEE J. Quantum Electron.*, vol. 24, no. 2, pp. 184–197, Feb. 1988.

[16] D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting Hertzian dipoles," *Appl. Phys. Lett.*, vol. 45, no. 3, pp. 284–286, Aug. 1984.

[17] P. R. Smith, D. H. Auston, and M. C. Nuss, "Subpicosecond photoconductive dipole antennas," *IEEE J. Quantum Electron.*, vol. 24, no. 2, pp. 255–260, Feb. 1988.

[18] B. B. Hu, X. C. Zhang, D. H. Auston, and P. R. Smith, "Free-space radiation from electrooptic crystals," *Appl. Phys. Lett.*, vol. 56, pp. 506–508, Feb. 1990.

[19] X. C. Zhang, B. B. Hu, J. T. Darrow, and D. H. Auston, "Generation of femtosecond electromagnetic pulses from semiconductor surfaces," *Appl. Phys. Lett.*, vol. 56, no. 11, pp. 1011–1013, Mar. 1990.

[20] B. B. Hu, J. T. Darrow, X. C. Zhang, D. H. Auston, and P. R. Smith, "Optically steerable photoconducting antennas," *Appl. Phys. Lett.*, vol. 56, pp. 886–888, Mar. 1990.

[21] J. T. Darrow, B. B. Hu, X. C. Zhang, and D. H. Auston, "Subpicosecond electromagnetic pulses from large-aperture photoconducting antennas," *Opt. Lett.*, vol. 15, pp. 323–325, Mar. 1990.

[22] J. T. Darrow, X. C. Zhang, and D. H. Auston, "Power scaling of large-aperture photoconducting antennas," *Appl. Phys. Lett.*, vol. 58, pp. 25–27, Jan. 1991.

[23] J. T. Darrow, X. C. Zhang, and J. D. Morse, "Saturation properties of large-aperture photoconducting antennas," *IEEE J. Quantum Electron.*, vol. 28, no. 6, pp. 1607–1618, Jun. 1992.

[24] X. C. Zhang *et al.*, "Optically induced electromagnetic-radiation from semiconductor surfaces," *Appl. Phys. Lett.*, vol. 56, pp. 2228–2230, May 1990.

[25] C. Shu, B. B. Hu, X. C. Zhang, P. Mei, and E. S. Yang, "Picosecond photoconductive response of polycrystalline silicon thin-films," *Appl. Phys. Lett.*, vol. 57, pp. 64–66, Jul. 1990.

[26] X. C. Zhang, B. B. Hu, S. H. Xin, and D. H. Auston, "Optically induced femtosecond electromagnetic pulses from GaSb/AlSb strained-layer superlattices," *Appl. Phys. Lett.*, vol. 57, pp. 753–755, Aug. 1990.

[27] B. B. Hu, X. C. Zhang, and D. H. Auston, "Temperature-dependence of femtosecond electromagnetic-radiation from semiconductor surfaces," *Appl. Phys. Lett.*, vol. 57, pp. 2629–2631, Dec. 1990.

[28] N. Froberg, M. Mack, B. B. Hu, X. C. Zhang, and D. H. Auston, "500 GHz electrically steerable photoconducting antenna-array," *Appl. Phys. Lett.*, vol. 58, pp. 446–448, Feb. 1991.

[29] B. B. Hu, N. Froberg, M. Mack, X. C. Zhang, and D. H. Auston, "Electrically controlled frequency scanning by a photoconducting antenna-array," *Appl. Phys. Lett.*, vol. 58, pp. 1369–1371, Apr. 1991.

[30] N. M. Froberg, B. B. Hu, X. C. Zhang, and D. H. Auston, "Terahertz radiation from a photoconducting antenna-array," *IEEE J. Quantum Electron.*, vol. 28, no. 10, pp. 2291–2301, Oct. 1992.

[31] N. M. Froberg, B. B. Hu, X. C. Zhang, and D. H. Auston, "Time-division multiplexing by a photoconducting antenna-array," *Appl. Phys. Lett.*, vol. 59, pp. 3207–3209, Dec. 1991.

[32] C. Shu, X. C. Zhang, E. S. Yang, and D. H. Auston, "Optoelectronic generation of time-division multiplexed ultrafast bit stream on a coplanar wave-guide," *Appl. Phys. Lett.*, vol. 57, pp. 2897–2898, Dec. 1990.

[33] X. C. Zhang and D. H. Auston, "Generation of steerable submillimeter waves from semiconductor surfaces by spatial light modulators," *Appl. Phys. Lett.*, vol. 59, pp. 768–770, Aug. 1991.

[34] L. Xu, X. C. Zhang, D. H. Auston, and B. Jalali, "Terahertz radiation from large aperture Si P-I-N-diodes," *Appl. Phys. Lett.*, vol. 59, pp. 3357–3359, Dec. 1991.

[35] C. Shu, X. Wu, E. S. Yang, X. C. Zhang, and D. H. Auston, "Propagation characteristics of picosecond electrical pulses on a periodically loaded coplanar wave-guide," *IEEE Trans. Microw. Theory Techn.*, vol. 39, no. 6, pp. 930–936, Jun. 1991.

[36] L. Xu, X. C. Zhang, D. H. Auston, and W. I. Wang, "Internal piezoelectric fields in GaInSb/InAs strained-layer superlattices probed by optically induced microwave-radiation," *Appl. Phys. Lett.*, vol. 59, pp. 3562–3564, Dec. 1991.

[37] P. M. Ferm *et al.*, "Femtosecond response of electrooptic poled polymers," *Appl. Phys. Lett.*, vol. 59, pp. 2651–2653, Nov. 1991.

[38] X. C. Zhang and D. H. Auston, "Optoelectronic measurement of semiconductor surfaces and interfaces with femtosecond optics," *J. Appl. Phys.*, vol. 71, pp. 326–338, Jan. 1992.

[39] X. C. Zhang, Y. Jin, B. B. Hu, X. Li, and D. H. Auston, "Optoelectronic study of piezoelectric field in strained-layer superlattices," *Superlattices Microstruct.*, vol. 12, no. 4, pp. 487–490, 1992.

[40] X. C. Zhang and D. H. Auston, "Optically induced THz electromagnetic-radiation from planar photoconducting structures," *J. Electromagn. Waves Appl.*, vol. 6, pp. 85–106, 1992.

[41] L. Xu, X. C. Zhang, and D. H. Auston, "Terahertz beam generation by femtosecond optical pulses in electrooptic materials," *Appl. Phys. Lett.*, vol. 61, pp. 1784–1786, Oct. 1992.

[42] K. H. Yang, P. L. Richards, and Y. R. Shen, "Generation of far-infrared radiation by picosecond light pulses in $LiNbO_3$," *Appl. Phys. Lett.*, vol. 19, pp. 320–322, Nov. 1971.

[43] X. C. Zhang, Y. Jin, K. Yang, and L. J. Schowalter, "Resonant nonlinear susceptibility near the GaAs band-gap," *Physical Rev. Lett.*, vol. 69, no. 15, pp. 2303–2306, 1992.

[44] S. Wu, X. C. Zhang, and R. L. Fork, "Direct experimental-observation of interactive 3rd and 5th order nonlinearities in a time-resolved and space-resolved 4-wave-mixing experiment," *Appl. Phys. Lett.*, vol. 61, pp. 919–921, Aug. 1992.

[45] X. C. Zhang, Y. Jin, and X. F. Ma, "Coherent measurement of THz optical rectification from electrooptic crystals," *Appl. Phys. Lett.*, vol. 61, pp. 2764–2766, Dec. 1992.

[46] X. C. Zhang *et al.*, "Terahertz optical rectification from a nonlinear organic-crystal," *Appl. Phys. Lett.*, vol. 61, pp. 3080–3082, Dec. 1992.

[47] X. F. Ma and X. C. Zhang, "Determination of ratios between nonlinear-optical coefficients by using subpicosecond optical rectification," *J. Opt. Soc. Amer. B—Opt. Phys.*, vol. 10, pp. 1175–1179, Jul. 1993.

[48] P. H. Siegel, "Terahertz pioneer: Hiromasa Ito—Generating THz energy is crystal clear," *IEEE Trans. THz Sci. Technol.*, vol. 5, no. 1, pp. 6–13, Jan. 2015.

[49] X. C. Zhang, Y. Jin, T. D. Hewitt, T. Sangsiri, L. E. Kingsley, and M. Weiner, "Magnetic switching of THz beams," *Appl. Phys. Lett.*, vol. 62, pp. 2003–2005, Apr. 1993.

[50] X. C. Zhang *et al.*, "Difference-frequency-generation and sum-frequency generation near the band-gap of zincblende crystals," *Appl. Phys. Lett.*, vol. 64, pp. 622–624, Jan. 1994.

[51] A. Rice *et al.*, "Terahertz optical rectification from (110) zincblende crystals," *Appl. Phys. Lett.*, vol. 64, pp. 1324–1326, Mar. 1994.

[52] Y. Jin, X. F. Ma, G. A. Wagoner, M. Alexander, and X. C. Zhang, "Anomalous optically generated THz beams from metal GaAs interfaces," *Appl. Phys. Lett.*, vol. 65, pp. 682–684, Aug. 1994.

[53] X.-C. Zhang, "Generation and detection of THz EM pulse from dielectrics with femtosecond optics," in *Ultra-Fast Phenomena*, ser. CCAST-WL, K. Shum, Y. J. Ding, and X. Zhang, Eds. Philadelphia, PA, USA: Gordon and Breach, 1994, vol. 38, pp. 89–115.

[54] X.-C. Zhang, "Generation and detection of terahertz electromagnetic pulsed radiation from semiconductor crystals with femtosecond optics," in *Compound Optoelectronic Materials and Devices*. Sydney, Australia: Semiconductor Science and Technol. Labs, 1995, vol. 69.

[55] X. C. Zhang, "Generation and detection of terahertz electromagnetic pulses from semiconductors with femtosecond optics," *J. Luminesc.*, vol. 66–7, pp. 488–492, Dec. 1995.

[56] M. Li, F. G. Sun, G. A. Wagoner, M. Alexander, and X. C. Zhang, "Measurement and analysis of terahertz radiation from bulk semiconductors," *Appl. Phys. Lett.*, vol. 67, pp. 25–27, Jul. 1995.

[57] F. G. Sun, G. A. Wagoner, and X. C. Zhang, "Measurement of free-space terahertz pulses via long-lifetime photoconductors," *Appl. Phys. Lett.*, vol. 67, pp. 1656–1658, Sep. 1995.

[58] X.-C. Zhang and Y. Jin, "THz electromagnetic radiation from dielectrics," in *Perspectives in Optoelectronics*. Singapore: World Scientific, 1995, ch. 3, pp. 81–138.

[59] Q. Wu and X. C. Zhang, "Free-space electrooptic sampling of terahertz beams," *Appl. Phys. Lett.*, vol. 67, pp. 3523–3525, Dec. 1995.

[60] Q. Wu, M. Litz, and X. C. Zhang, "Broadband detection capability of ZnTe electro-optic field detectors," *Appl. Phys. Lett.*, vol. 68, pp. 2924–2926, May 1996.

[61] Q. Wu, F. G. Sun, P. Campbell, and X. C. Zhang, "Dynamic range of an electro-optic field sensor and its imaging applications," *Appl. Phys. Lett.*, vol. 68, pp. 3224–3226, Jun. 1996.

[62] Q. Wu and X. C. Zhang, "Electrooptic sampling of freely propagating terahertz fields," *Opt. Quantum Electron.*, vol. 28, pp. 945–951, Jul. 1996.

[63] Q. Wu and X. C. Zhang, "Design and characterization of traveling-wave electrooptic terahertz sensors," *IEEE J. Sel. Topics in Quantum Electron.*, vol. 2, no. 5, pp. 693–700, Sep./Oct. 1996.

[64] Q. Wu, T. D. Hewitt, and X. C. Zhang, "Two-dimensional electro-optic imaging of THz beams," *Appl. Phys. Lett.*, vol. 69, pp. 1026–1028, Aug. 1996.

[65] Q. Wu and X. C. Zhang, "Free-space electro-optics sampling of mid-infrared pulses," *Appl. Phys. Lett.*, vol. 71, pp. 1285–1286, Sep. 1997.

[66] Q. Wu and X. C. Zhang, "7 terahertz broadband GaP electro-optic sensor," *Appl. Phys. Lett.*, vol. 70, pp. 1784–1786, Apr. 1997.

[67] Z. G. Lu, P. Campbell, and X. C. Zhang, "Free-space electro-optic sampling with a high-repetition-rate regenerative amplified laser," *Appl. Phys. Lett.*, vol. 71, pp. 593–595, Aug. 1997.

[68] J. A. Riordan, F. G. Sun, Z. G. Lu, and X. C. Zhang, "Free-space transient magneto-optic sampling," *Appl. Phys. Lett.*, vol. 71, pp. 1452–1454, Sep. 1997.

[69] H. J. Bakker, G. C. Cho, H. Kurz, Q. Wu, and X. C. Zhang, "Distortion of terahertz pulses in electro-optic sampling," *J. tOpt. Soc. Amer. B—Opt. Phys.*, vol. 15, pp. 1795–1801, Jun. 1998.

[70] P. Y. Han and X. C. Zhang, "Coherent, broadband midinfrared terahertz beam sensors," *Appl. Phys. Lett.*, vol. 73, pp. 3049–3051, Nov. 1998.

[71] Z. P. Jiang and X.-C. Zhang, "Free-space electro-optic technologies," in *A Chapter in THz Sensing and Imaging Technol*, ser. Springer Series in Optical Sciences, D. Mittleman, Ed. New York: Springer, 2002, pp. 155–192.

[72] Q. Chen and X.-C. Zhang, "Electro-optic THz imaging," in *Ultrafast Lasers: Technol. and Applications*, Fermann, Galvanauskas, and Sucha, Eds. : Marcel Dekker, Inc., 2002, ch. Chapter 11, pp. 521–572.

[73] S. P. Mickan and X.-C. Zhang, "T-ray sensing and imaging," in *Terahertz Sensing Technol.: Electronic Devices Advanced Technol.*, D. Woolard, M. S. Shur, and W. Leorop, Eds. Singapore: Word Scientific, 2003, ch. 8, pp. 351–326.

[74] Y. Cai, I. Brener, J. Lopata, J. Wynn, L. Pfeiffer, J. B. Stark, Q. Wu, X. C. Zhang, and J. F. Federici, "Coherent terahertz radiation detection: Direct comparison between free-space electro-optic sampling and antenna detection," *Appl. Phys. Lett.*, vol. 73, pp. 444–446, Jul. 1998.

[75] Z. P. Jiang and X. C. Zhang, "Electro-optic measurement of THz field pulses with a chirped optical beam," *Appl. Phys. Lett.*, vol. 72, pp. 1945–1947, Apr. 1998.

[76] F. G. Sun, Z. P. Jiang, and X. C. Zhang, "Analysis of terahertz pulse measurement with a chirped probe beam," *Appl. Phys. Lett.*, vol. 73, pp. 2233–2235, Oct. 1998.

[77] Z. P. Jiang and X. C. Zhang, "Single-shot spatiotemporal terahertz field imaging," *Opt. Lett.*, vol. 23, pp. 1114–1116, Jul. 1998.

[78] Z. P. Jiang and X. C. Zhang, "Single-shot measurement of a terahertz pulse," *Appl. Opt.*, vol. 37, pp. 8145–8146, Dec. 1998.

[79] Z. P. Jiang, F. G. Sun, and X. C. Zhang, "Terahertz pulse measurement with an optical streak camera," *Opt. Lett.*, vol. 24, pp. 1245–1247, Sep. 1999.

[80] Z. P. Jiang and X. C. Zhang, "2D measurement and spatio-temporal coupling of few-cycle THz pulses," *Opt. Express*, vol. 5, pp. 243–248, Nov. 1999.

[81] Z. P. Jiang and X. C. Zhang, "Terahertz imaging via electrooptic effect," *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 12, pp. 2644–2650, Dec. 1999.

[82] Z. P. Jiang and X. C. Zhang, "Measurement of spatio-temporal terahertz field distribution by using chirped pulse technology," *IEEE J. Quantum Electron.*, vol. 36, no. 10, pp. 1214–1222, Oct. 2000.

[83] P. Y. Han, G. C. Cho, and X.-C. Zhang, "Study of coherent THz-transillumination for biological tissue imaging," in *OSA Annu. Meeting*, Santa Clara, CA, USA, Sep. 30, 1999.

[84] X. G. Huang, G. Carosi, P. Persans, and X.-C. Zhang, "Optical characterization of thin dielectric waveguides," in *LEOS'99 Annu. Meeting*, San Francisco, CA, Nov. 8–11, 1999.

[85] J. A. Riordan and X.-C. Zhang, "Transient magneto-optic sampling in liquids," in *Ultrafast Electronics and Optoelectronics*, J. Bowers and W. Knox, Eds. : , 1999, vol. 28, OSA Trends in Optics and Photonics, Optical Society of America.

[86] Q. Chen, Z. Jiang, G. Xu, and X.-C. Zhang, "Applications of terahertz time-domain measurement on paper currencies," *Lasers and Electro-optics*, vol. 2, pp. 547–548, 1999.

[87] X.-C. Zhang, "Optoelectronic THz imaging," in *Plenary talk, 24th Int. Conf. Infrared Millim. Waves*, Monterey, CA, USA, Sep. 8, 1999.

[88] M. Li, G. C. Cho, T. M. Lu, X. C. Zhang, S. Q. Wang, and J. T. Kennedy, "Time-domain dielectric constant measurement of thin film in GHz-THz frequency range near the Brewster angle," *Appl. Phys. Lett.*, vol. 74, pp. 2113–2115, Apr. 1999.

[89] M. Li, X. C. Zhang, G. Sucha, and D. J. Harter, "Portable THz system and its applications," in *Commercial and Biomedical Applications of Ultrafast Lasers*, M. K. Reed and J. Neev, Eds. : , 1999, vol. 3616, pp. 126–135.

[90] Q. Chen, Z. P. Jiang, M. Tani, and X. C. Zhang, "Electro-optic terahertz transceiver," *Electron. Lett.*, vol. 36, pp. 1298–1299, Jul. 2000.

[91] Q. Chen, Z. P. Jiang, G. X. Xu, and X. C. Zhang, "Near-field terahertz imaging with a dynamic aperture," *Opt. Lett.*, vol. 25, pp. 1122–1124, Aug. 2000.

[92] P. Y. Han, G. C. Cho, and X. C. Zhang, "Time-domain transillumination of biological tissues with terahertz pulses," *Opt. Lett.*, vol. 25, pp. 242–244, Feb. 2000.
[93] P. Y. Han, M. Tani, F. Pan, and X. C. Zhang, "Use of the organic crystal DAST for terahertz beam applications," *Opt. Lett.*, vol. 25, pp. 675–677, May 2000.
[94] R. McLaughlin *et al.*, "Enhanced coherent terahertz emission from indium arsenide," *J. Modern Opt.*, vol. 47, pp. 1847–1856, Sep. 2000.
[95] S. Mickan, D. Abbott, J. Munch, X. C. Zhang, and T. van Doorn, "Analysis of system trade-offs for terahertz imaging," *Microelectron. J.*, vol. 31, pp. 503–514, Jul. 2000.
[96] M. Tani, K. S. Lee, and X. C. Zhang, "Detection of terahertz radiation with low-temperature-grown GaAs-based photoconductive antenna using 1.55 mu M probe," *Appl. Phys. Lett.*, vol. 77, pp. 1396–1398, Aug. 2000.
[97] Q. Chen, M. Tani, Z. P. Jiang, and X. C. Zhang, "Electro-optic transceivers for terahertz-wave applications," *J. Opt. Soc. Amer. B—Opt. Phys.*, vol. 18, pp. 823–831, Jun. 2001.
[98] Q. Chen and X. C. Zhang, "Semiconductor dynamic aperture for near-field terahertz wave imaging," *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 4, pp. 608–614, Jul./Aug. 2001.
[99] M. Li, J. Fortin, J. Y. Kim, G. Fox, F. Chu, T. Davenport, T. M. Lu, and X. C. Zhang, "Dielectric constant measurement of thin films using goniometric terahertz time-domain spectroscopy," *IEEE J. Sel. Topics Quantum Electron.*, vol. 7, no. 4, pp. 624–629, Jul./Aug. 2001.
[100] B. Ferguson, S. H. Wang, D. Gray, D. Abbott, and X. C. Zhang, "Terahertz imaging of biological tissue using a chirped probe pulse," in *Electronics and Structures for MEMs II*, N. W. Bergmann, D. Abbott, A. J. Hariz, and V. K. Varadan, Eds., 2001, vol. 4591, pp. 172–184.
[101] P. Y. Han, M. Tani, M. Usami, S. Kono, R. Kersting, and X. C. Zhang, "A direct comparison between terahertz time-domain spectroscopy and far-infrared Fourier transform spectroscopy," *J. Appl. Phys.*, vol. 89, pp. 2357–2359, Feb. 2001.
[102] X. C. Zhang, K. S. Lee, X. C. Zhang, X. Wei, and Y. R. Shen, "Optical constants of ice IH crystal at terahertz frequencies," *Appl. Phys. Lett.*, vol. 79, pp. 491–493, Jul. 2001.
[103] Y. C. Chen, N. R. Raravikar, L. S. Schadler, P. M. Ajayan, Y. P. Zhao, T. M. Lu, G.-C. Wang, and X.-C. Zhang, "Ultrafast optical switching properties of single-wall carbon nanotube polymer composites at 1.55 μm," *Appl. Phys. Lett.*, vol. 81, pp. 975–977, Aug. 2002.
[104] B. Ferguson, S. Wang, D. Gray, D. Abbott, and X. C. Zhang, "Identification of biological tissue using chirped probe THz imaging," *Microelectron. J.*, vol. 33, pp. 1043–1051, Dec. 2002.
[105] B. Ferguson, S. H. Wang, D. Gray, D. Abbott, and X. C. Zhang, "T-ray tomographic imaging," in *Biomed. Appl. Micro-and Nanoeng.*, D. V. Nicolau and A. P. Lee, Eds., 2002, vol. 4937, pp. 62–72.
[106] B. Ferguson, S. H. Wang, D. Gray, D. Abbot, and X. C. Zhang, "T-ray computed tomography," *Opt. Lett.*, vol. 27, pp. 1312–1314, Aug. 2002.
[107] B. Ferguson and X. C. Zhang, "Materials for terahertz science and technology," *Nature Mater.*, vol. 1, pp. 26–33, Sep. 2002.
[108] P. Gu, M. Tani, S. Kono, K. Sakai, and X. C. Zhang, "Study of terahertz radiation from InAs and InSb," *J. Appl. Phys.*, vol. 91, pp. 5533–5537, May 2002.
[109] K. Liu, H. S. Kang, T. K. Kim, and X. C. Zhang, "Study of ZnCdTe crystals as terahertz wave emitters and detectors," *Appl. Phys. Lett.*, vol. 81, pp. 4115–4117, Nov. 2002.
[110] S. P. Mickan, J. Dordick, J. Munch, D. Abbott, and X. C. Zhang, "Terahertz spectroscopy of bound water in nano suspensions," in *Biomed. Appl. Micro-and Nanoeng.*, D. V. Nicolau and A. P. Lee, Eds., 2002, vol. 4937, pp. 49–61.
[111] E. D. Walsby *et al.*, "Multilevel silicon diffractive optics for terahertz waves," *J. Vac. Sci. Technol. B*, vol. 20, pp. 2780–2783, Nov.-Dec. 2002.
[112] S. Wang *et al.*, "Characterization of T-ray binary lenses," *Opt. Lett.*, vol. 27, pp. 1183–1185, Jul. 2002.
[113] J. Z. Xu and X. C. Zhang, "Optical rectification in an area with a diameter comparable to or smaller than the center wavelength of terahertz radiation," *Opt. Lett.*, vol. 27, pp. 1067–1069, Jun. 2002.
[114] "New laboratory to expand terahertz research at RPI," in *Schenectady Daily Gazette*. : News in Brief, 2002, p. B-04.
[115] B. McGuire, "RPI dedicates 'terahertz' center, $15 million facility will research the electromagnetic spectrum," *Schenectady Daily Gazette*, p. C-01, Dec. 2003.
[116] P. H. Siegel, "Terahertz pioneer: Daniel R. Grischkowsky—We search for truth and beauty," *IEEE Trans. THz Sci. Technol.*, vol. 2, no. 4, pp. 377–382, Jul. 2012.
[117] P. H. Siegel, "Terahertz pioneer: Paul L. Richards—Working at the edge—transition edge sensors and the edge of the universe," *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 2, pp. 341–348, Nov. 2011.
[118] P. H. Siegel, "Terahertz pioneer: Michael Bass—The THz light at the end of the tunnel," *IEEE Trans. THz Sci. Technol.*, vol. 4, no. 4, pp. 409–416, Jul. 2014.
[119] C. Zandonella, "Terahertz imaging: T-ray specs," *Nature, News Feature*, vol. 424, pp. 721–722, Aug. 2003.
[120] B. McGuire, "RPI team detects defects in foam T-ray technology could help NASA," *Schenectady Daily Gazette*, p. C-01, Jun. 2003.
[121] T. Yuan, H. Zhong, X. J. Xu, X.-C. Zhang, E. Madaras, and R. Reightler, "Detection of defects in space shuttle by THz technol," *CenSSIS Ind. Application*, Nov. 2003.
[122] H. Zhong, N. Karpowicz, J. Xu, Y. Deng, W. Ussery, M. Shur, and X.-C. Zhang, "Detection of space shuttle insulation foam defects by using a 0.2 THz Gunn diode oscillator and pyroelectric detector," in *Joint 29th Int. Conf. on Infrared and Millimeter Waves and 12th Int. Conf. on THz Electron.*, Karlsruhe, Germany, Sep. 30, 2004.
[123] Y. Chen, H. Liu, Y. Deng, D. B. Veksler, M. S. Shur, X.-C. Zhang, D. Schauki, M. J. Fitch, and R. Osiander, "Spectroscopic characterization of explosives," in *SPIE Defense and Security Symp. 2004*, Orlando, FL, Apr. 12, 2004, vol. 5411–02.
[124] S. H. Wang, B. Ferguson, D. Abbott, and X.-C. Zhang, "T-RAY imaging and tomography," *J. Biological Physics*, vol. 29, no. 2-3, pp. 247–256, 2003.
[125] J. B. Spicer, P. Dagdigian, R. Osiander, J. A. Miragliotta, X.-C. Zhang, R. Kersting, D. R. Crosley, and R. K. Hanson, "Johns Hopkins Univ. Rensselaer Polytechnic Institute; SRI international; Stanford Univ., Overview: MURI center on spectroscopic and time domain detection of trace explosives in condensed and vapor phases," in *SPIE's Aerosense, Battlefield Technologies Conf.*, Florida, Apr. 25, 2003, pp. 5089–120.
[126] Y. Q. Deng, R. Kersting, J. Z. Xu, R. Ascazubi, X. C. Zhang, M. S. Shur, R. Gaska, G. S. Simin, M. A. Khan, and V. Ryzhii, "Millimeter wave emission from GaN high electron mobility transistor," *Appl. Phys. Lett.*, vol. 84, pp. 70–72, Jan. 2004.
[127] K. Liu, J. Z. Xu, and X. C. Zhang, "GaSe crystals for broadband terahertz wave detection," *Appl. Phys. Lett.*, vol. 85, pp. 863–865, Aug. 2004.
[128] N. Karpowicz, H. Zhong, C. L. Zhang, K. I. Lin, J. S. Hwang, J. Z. Xu, and X. C. Zhang, "Compact continuous-wave subterahertz system for inspection applications," *Appl. Phys. Lett.*, vol. 86, Jan. 2005.
[129] N. Karpowicz, H. Zhong, J. Z. Xu, K. I. Lin, J. S. Hwang, and X. C. Zhang, "Comparison between pulsed terahertz time-domain imaging and continuous wave terahertz imaging," *Semiconductor Sci. and Technol.*, vol. 20, pp. S293–S299, Jul. 2005.
[130] F. Teppe *et al.*, "Plasma wave resonant detection of femtosecond pulsed terahertz radiation by a nanometer field-effect transistor," *Appl. Phys. Lett.*, vol. 87, Jul. 2005.
[131] H. Zhong *et al.*, "Nondestructive defect identification with terahertz time-of-flight tomography," *IEEE Sensors J.*, vol. 5, no. 2, pp. 203–208, Apr. 2005.
[132] H. B. Liu, Y. Q. Chen, G. J. Bastiaans, and X. C. Zhang, "Detection and identification of explosive RDX by THz diffuse reflection spectroscopy," *Opt. Express*, vol. 14, pp. 415–423, Jan. 2006.
[133] H. Zhong, A. Redo-Sanchez, and X. C. Zhang, "Identification and classification of chemicals using terahertz reflective spectroscopic focal-plane imaging system," *Opt. Express*, vol. 14, pp. 9130–9141, Oct. 2006.
[134] J. Chen, Y. Q. Chen, H. W. Zhao, G. J. Bastiaans, and X. C. Zhang, "Absorption coefficients of selected explosives and related compounds in the range of 0.1–2.8 THz," *Opt. Express*, vol. 15, pp. 12060–12067, Sep. 2007.
[135] H. Zhong, N. Karpowicz, and X. C. Zhang, "Terahertz emission profile from laser-induced air plasma," *Appl. Phys. Lett.*, vol. 88, Jun. 2006.
[136] N. Karpowicz *et al.*, "Coherent heterodyne time-domain spectrometry covering the entire, terahertz gap," *Appl. Phys. Lett.*, vol. 92, Jan. 2008.
[137] J. L. Liu, J. M. Dai, S. L. Chin, and X. C. Zhang, "Broadband terahertz wave remote sensing using coherent manipulation of fluorescence from asymmetrically ionized gases," *Nature Photon.*, vol. 4, pp. 627–631, Sep. 2010.
[138] H. B. Liu, H. Zhong, N. Karpowicz, Y. Q. Chen, and X. C. Zhang, "Terahertz spectroscopy and imaging for defense and security applications," *Proc. IEEE*, vol. 95, no. 8, pp. 1514–1527, Aug. 2007.
[139] H. Hamster, A. Sullivan, S. Gordon, W. White, and R. W. Falcone, "Subpicosecond, electromagnetic pulses from intense laser-plasma interaction," *Phys. Rev. Lett.*, vol. 71, pp. 2725–2728, 1993.

[140] H. Hamster, A. Sullivan, S. Gordon, and R. W. Falcone, "Short pulse terahertz radiation from high-intensity-laser-produced plasmas," *Physical Rev. E*, vol. 49, no. 1, pp. 671–677, Jan. 1994.
[141] T. Löffler, F. Jacob, and H. G. Roskos, "Generation of terahertz pulses by photoionization of electrically biased air," *Appl. Phys. Lett.*, vol. 77, no. 3, pp. 453–455, 2000.
[142] D. J. Cook and R. M. Hochstrasser, "Intense terahertz pulses by four-wave rectification in air," *Opt. Lett.*, vol. 25, pp. 1210–1212, 2000.
[143] X. Xie, J. M. Dai, and X. C. Zhang, "Coherent control of THz wave generation in ambient air," *Physical Rev. Lett.*, vol. 96, no. 075005, pp. 075005-1–075005-4, Feb. 2006.
[144] J. Dai, X. Xie, and X. C. Zhang, "Detection of broadband terahertz waves with a laser-induced plasma in gases," *Physical Rev. Lett.*, vol. 97, no. 10, pp. 103903-1–103903-4, 2006.
[145] X. Xie, J. M. Dai, M. Yamaguchi, and X.-C. Zhang, "Ambient air used as the nonlinear media for THz wave generation," *Select. Topics in Electrics Syst.,*, vol. 46, THz Sci. Technol. for Military and Security Application, p. 69, 2007.
[146] X. Xie, J. Z. Xu, J. M. Dai, and X. C. Zhang, "Enhancement of terahertz wave generation from laser induced plasma," *Appl. Phys. Lett.*, vol. 90, Apr. 2007.
[147] J. M. Dai and X. C. Zhang, "Terahertz wave generation from gas plasma using a phase compensator with attosecond phase-control accuracy," *Appl. Phys. Lett.*, vol. 94, Jan. 2009.
[148] X. C. Zhang, "Air photonics: Tera-mid infrared radiation," in *Terahertz and Mid Infrared Radiation: Generation, Detection and Applications*, M. F. Pereira and O. Shulika, Eds. Berlin, Germany: Springer, 2009, pp. 195–202.
[149] X.-C. Zhang and J. Xu*, Introduction to Terahertz Wave Photonics*. Berlin, Germany: Springer, 2010.
[150] T. A. Elkhatib *et al.*, "Enhanced plasma wave detection of terahertz radiation using multiple high electron-mobility transistors connected in series," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 2, pp. 331–339, Feb. 2010.
[151] X. F. Lu *et al.*, "Science, technology, and application of THz air photonics," in *Infrared, Millimeter Wave, and Terahertz Technologies*, C. Zhang, X. C. Zhang, P. H. Siegel, L. He, and S. C. Shi, Eds. Philadeplphia, PA, USA: SPIE, 2010, vol. 7854.
[152] J. L. Liu and X. C. Zhang, "Plasma characterization using terahertz-wave-enhanced fluorescence," *Appl. Phys. Lett.*, vol. 96, Jan. 2010.
[153] J. Liu, J. M. Dai, and X. C. Zhang, "Ultrafast broadband terahertz waveform measurement utilizing ultraviolet plasma photoemission," *J. Opt. Soc. Amer. B—Opt. Physics*, vol. 28, pp. 796–804, Apr. 2011.
[154] X.-C. Zhang, "Air photonics: Tera-Mid infrared radiation," in *Terahertz and Mid Infrared Radiation: Generation, Detection and Applications*, M. F. Pereira and O. Shulika, Eds. New York, NY, USA: Springer, 2011, ch. 28.
[155] B. Clough, J. L. Liu, and X. C. Zhang, "'All air-plasma' terahertz spectroscopy," *Opt. Lett.*, vol. 36, pp. 2399–2401, Jul. 2011.
[156] J. M. Dai, J. Liu, and X. C. Zhang, "Terahertz wave air photonics: Terahertz wave generation and detection with laser-induced gas plasma," *IEEE J. Sel. Topics Quantum Electron.*, vol. 17, no. 1, pp. 183–190, Jan./Feb. 2011.
[157] J. M. Dai and X. C. Zhang, "Standoff terahertz wave generation from two-color laser-induced plasma at 30 meters in ambient air," in *36th Int. Conf. Infrared, Millim., THz Waves (IRMMW-THz2011)*, 2011.
[158] X.-C. Zhang, "Terahertz wave air photonics: Bridging the gap and beyond," in *Laser and Photon. Syst.: Des. Integr.*, Nof, Weiner, and Cheng, Eds. : CRC Press, 2013, ch. 8, pp. 141–164.
[159] X. Sun and X. C. Zhang, "Terahertz radiation in alkali vapor plasmas," *Appl. Phys. Lett.*, vol. 104, May 2014.
[160] F. Buccheri and X. C. Zhang, "Terahertz emission from laser-induced microplasma in ambient air," *Optica*, vol. 2, pp. 366–369, Apr. 2015.
[161] X.-C. Zhang, "Special Issue on Terahertz Wave Science Technology and Application, ," *Frontiers of Optoelectron.*, vol. 7, no. 2, Jun. 2014.

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