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 composing them.

This month we cross the Pacific to hear the story of a young electrical engineer from Japan who was so self-motivated, he used his mother's inheritance to cover the cost of attending the very first international THz symposium, held in Brooklyn, NY, USA, back in March 1970. Ever since that career forming decision to participate in something new and exciting, Professor Koji Mizuno has been an active contributor to THz science and applications. Back in 1970, the appropriate terminology was submillimeter waves. Nevertheless, the discipline spanned a very wide application base and attracted a diverse group of scientists, which included chemists, physicists, engineers and even one or two biologists. Professor Mizuno worked in all of these areas, and as we shall find, has been one of the staunchest supporters of our discipline, as well as a tireless ambassador that has helped to bring the science of THz to Asia and beyond.

PETER H. SIEGEL, *Editor-in-Chief*
Departments of Biology and
Electrical Engineering
California Institute of Technology

Senior Research Scientist
NASA Jet Propulsion Laboratory
Pasadena, CA 91125 USA

On November 30th, 2012, Sensei Mizuno-san took a significant detour on his way back from a conference in Yokohama to meet me in the Tokyo/Narita International airport, where I too was returning from a conference event in Nara. With the help of a former student, now at the Ministry of Transportation in Japan, Professor Mizuno and I were able to find a quiet room at the Departures terminal where we spent several wonderful hours discussing his life and his career in THz science and applications. The result is this brief biographical sketch of a person who has spent almost a half-century working on submillimeter-waves.

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Terahertz Pioneer: Koji Mizuno

"50 Years in Submillimeter-Waves: From Otaku to Sensei"

Peter H. Siegel, *Fellow, IEEE*

BORN IN SAPPORO, Hokkaido, Japan, in 1940, Koji Mizuno[1] remembers well the difficult times Japanese children faced in the aftermath of World War II. The son of an educated lawyer, who found work as a newspaper reporter, and a very well-known Japanese doll maker, young Koji was reading whatever his father would bring home from work, even before the age of 10. This included occasional scientific journals, one of which he recalls, had wonderful photos of stars and galaxies taken by Caltech's newly operational 200 inch Hale telescope at Mt. Palomar Observatory, California, which saw first light in January 1949, when the famous Edwin Hubble took the initial astronomical exposures [1].

As a young teenager, Mizuno was encouraged by his mother to learn English, both in school and through a neighborhood church program. He was fascinated by electronics and was known locally as otaku, loosely translated as "radio boy." This early interest in technology was to serve him well, and at age 18, Mizuno entered Tohoku University, Sendai, Japan, where Shintaro Uda (Yagi-Uda antenna [2]) and Yasushi Watanabe (Yagi protégé, and early transistor pioneer in Japan) were still teaching.

In 1958, the department of Electronics Engineering at Tohoku was only two years old, and there was a strong tradition of microwave tube development, led by Yujiro Koike [3]. Mizuno did a Masters' thesis on channel electron multipliers [4] (a semiconductor-lined curved ceramic tube which produces a cascade of emitted electrons as an impinging beam bounces multiple times along the wall).

Mizuno then started working with Tohoku Professor Shoichi Ono, on a newly proposed high power tube [5]–[7] with an open cavity structure. He would later name it the "Ledatron" [8]–[10], after Leda, the mythological mother of two sets of simultaneous twins: divine twins born from Zeus (Helen of Troy and Pollux), and mortal twins born of Sparta's king Tyndareus (Castor and Clytemnestra—wife of Agamemnon).

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The author is with the Departments of Biology and Electrical Engineering at the California Institute of Technology, Pasadena, CA 91125 USA, and the NASA Jet Propulsion Laboratory, Pasadena, CA 91109 USA (e-mail: phs@caltech.edu).

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[1]On November 30th, 2012, **Sensei Mizuno-san** took a significant detour on his way back from a conference in Yokohama to meet me in the Tokyo/Narita International airport, where I too was returning from a conference event in Nara. With the help of a former student, now at the Ministry of Transportation in Japan, Professor Mizuno and I were able to find a quiet room at the departures terminal where we spent several wonderful hours discussing his life and his career in THz science and applications. The result is this brief biographical sketch of a person who has spent almost a half-century working on submillimeter-waves.

KOJI MIZUNO

The Ledatron was so named because it involved twin interactions in the electron stream: an open resonator interaction (Fabry–Pérot mode) and a surface wave interaction with a grooved metallic grating. Mizuno discovered that the two modes existed together and could be separated and tuned individually [8], one through mechanical adjustment of the resonator (via mirror spacing) and the other through electronic adjustment of the beam voltage. The Ledatron sends a high voltage electron stream across a precision metallic grating (stimulated emission from the Smith–Purcell effect—interaction of charged particles passing over a diffraction grating), and then adds an enclosing mirror to form an additional Fabry–Pérot type resonator. The Fabry–Pérot mode composes an electron-beam interaction with a standing electromagnetic wave in the resonator, and the surface wave mode is a backward wave interaction of the electron stream with the grating fields.

Fabricating the Ledatron was no easy task. Tolerances and scale size for the grating were severe. More than 100 small grooves with a width of only 25 microns and tolerances of 1 micron or better, had to be hand milled into the 5×5 cm metal form. There was a tradition in Tohoku at the time, that scientists should make their own instruments. Mizuno recalls that he continuously smelled of machine oil for the year it took him to finalize his first working oscillator!

The Ledatron was the first open structure, high power tube, capable of generating broadly tunable submillimeter waves using the two separable modes. In their 1973 paper [8], Mizuno, Ono and Shibata observed tunable (40% bandwidth) continuous wave power above 1 W at short millimeter wavelengths, and several hundred milliwatts above 300 GHz. The Ledatron was a significant breakthrough in early THz power generation, and rivaled a very similar structure—the orotron [11], [12] in implementation and performance.

After receiving his doctorate in 1968, Mizuno took up a position at Tohoku as a research associate working with Professor Yukio Shibata. He was very interested in *submillimeter-waves* for the same reasons many people are attracted to *THz* today—it was an exotic sounding new topic in electronics.

In late 1969, Mizuno saw an announcement in a journal that was advertising a conference on Submillimeter Waves to take place in the United States the next spring. Despite the fact that very few Japanese went abroad for conferences at the time, he decided to submit a paper on his Ledatron work. His earlier training in English would help of course, but the more amazing aspect of this decision, was the fact that he would have to pay his own way to NYC—department funding was not available to him. A year earlier, Mizuno's mother had passed away and she left him a small wedding fund, which she hoped her son would use to advance his worldview. Mizuno used this gift to finance his travel, and he became the only Japanese delegate to present at this first *International Symposium on Submillimeter Waves* at Brooklyn Polytechnic University in NYC in April 1970 [13]. This bold decision was to change Mizuno's life, and launch him on a long, internationally recognized career in submillimeter waves.

Mizuno practiced his presentation [14] many times and made a real impact at the conference. T. Misawa (Bell Laboratories well known expert on impact oscillators—*Misawa diodes*), even came up to Mizuno to compliment him on his presentation and his excellent English. While in the US, he also met and visited MIT's Ken Button, later Chair of the long running *Infrared and Millimeter Waves* conference series, Editor of the *International Journal of Infrared and Millimeter Waves* and, with Academic Press, publisher of the well known series of 16 technical books on submillimeter waves, *Infrared and Millimeter Waves*, between 1979 and 1986.

Soon after returning to Tohoku, Mizuno received a letter from Professor Derek Martin at Queen Mary College (Martin-Puplett interferometer [15]), asking if he would like to come to London under a UK Science Research Council fellowship to work on submillimeter wave sources. The trip was executed in 1972/73, and resulted in a set of nice review papers [16], [17].

The Ledatron work also led to several additional grating/electron stream concepts, including optical modulation of the RF beam resulting in large acceleration or amplification [18], [19], observations of the inverse Smith-Purcell effect [20] and a novel optical klystron [21]. Eventually the Ledatron was demonstrated as a spectroscope for submillimeter-wave measurements of solids, because of its wide tuning range and high source power [22].

Mizuno understood that sources were not the only hindrance to the development of submillimeter-wave applications. He had earlier worked on point-contact detectors [23], but like other THz pioneers [24], he soon realized that GaAs Schottky diodes, that were being developed for mixer and detector applications at millimeter-wavelengths, could be applied at higher frequencies given the right RF coupling conditions [25]. Mizuno's paper [26], on long wire antenna coupling to the diode via a "whisker contact" was a precursor for a very successful open structure "corner-cube" detector circuit [27]–[29] that held performance records for more than 2 decades, and can still be found in working order in many microwave laboratory cupboards today.

By the mid 1970's, semiconductor device processing had reached down to scales that could rival detector areas formerly achievable only through point contacts. Mizuno and others realized the benefit of fully planarizing these submillimeter wave components to add real performance repeatability as well as reliability (see discussion in [30] for example). In 1977 the first submillimeter wave planar diodes were realized and tested at MIT's Lincoln Labs [31]. In the same issue of IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, Mizuno and colleagues at Tohoku presented a design and frequency scaled model measurements for a planar Schottky diode detector structure with a dipole antenna and integrated feed lines [32]. Within a very short time, this and other planar antenna concepts took hold, and potentially realizable monolithic submillimeter-wave mixer and detector arrays became a ubiquitous proposal subject. It would take another three and a half decades however, before they became a functional reality [33]!

Mizuno and colleagues went on to design and test several other successful submillimeter-wave antenna and planar diode [34] concepts, including, appropriately, a planar version of the Yagi-Uda antenna [35] and a greatly improved slot antenna design with matching E and H plane patterns. The latter they termed the Fermi antenna [36] because the antenna taper, $f(x)$, follows a Fermi–Dirac distribution function: $f(x) = a/[1 + e^{-b(x-c)}]$, with a, b and c referring to specific geometric parameters.

By the late 1980's Mizuno began to get interested in RF imaging, and his focus shifted to millimeter wavelengths, where planar device technology was sufficiently developed to allow the prototyping of new instruments, and their use in real applications. During this time he proposed a novel mixture of solid-state devices embedded in a quasi-optical grid array with a Fabry–Pérot tuning element, reminiscent of the Ledatron configuration [37]. A quite similar concept was simultaneously invented, and very successfully exploited by Professor David Rutledge at Caltech [38]–[41], eventually resulting in a set of widely used commercial products [42]. In 1988, Rutledge visited Mizuno's laboratory at Tohoku University for six months, and in 1990, Mizuno came to Pasadena, CA, to work with Rutledge for an equal time period, and they have remained close friends ever since.

From 1990 to 1998, Mizuno took on an extra duty, serving as team leader, and then laboratory Director for the Photodynamics Research Center of the Institute for Physical and Chemical Research in Sendai (RIKEN). His research work focused more and more on millimeter-wave applications. He began applying imaging techniques to microscopy [43], [44], plasma diagnostics [45], data processing and reconstruction [46], biomedical problems [47], and even determining the water content and ripeness of fruits and vegetables [48].

As the submillimeter wave engineering community began to develop field deployable devices and instruments, the science applications spread into more and more disciplines, and Mizuno's millimeter-wave work was able to be extended to these higher frequencies. We now have THz near field microscopes, passive and active imagers and broad band spectrometers that are being used in many of the same application areas that prior millimeter-wave systems have explored.

Mizuno officially retired from Tohoku University in 2004, but he continues to work as a research professor, attending and participating in conferences and workshops as well as collaborating with many colleagues in Japan and elsewhere.

After appearing at the 1970 Submillimeter Wave symposium as the first THz researcher from Japan, Mizuno attended every subsequent submillimeter-wave conference under the *Infrared and Millimeter Wave* banner that Ken Button carried through to 2003, hosting one of these himself—the 19th in 1994 in Sendai, Japan. After the conference series expanded into the current *International Conference on Infrared, Millimeter and Terahertz Waves* [49] in 2004, he took on the role of the general Chair of the international organizing committee in 2006, and continued to remain active on the conference steering committee until 2011.

When I asked Professor Mizuno why he chose THz as his field of interest so many years ago, he replied (and I take the liberty of embellishing) that "*THz is a transition region, where physical phenomena cross over from one regime to another, and life is always concerned with transitions*." His advice to senior researchers (many of you will love this!) is to "please promote younger researchers." Finally, when I asked him who had the most influence on his career, he humbly replied that it was one of his early primary school teachers, who *treated everyone fairly, taught consideration for others, and made it clear that you had to grow by yourself*. Such a teacher we can all admire...

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Koji Mizuno received the B.Eng., M.Eng., and D.Eng. degrees in electronic engineering from Tohoku University, Sendai, Japan, in 1963, 1965, and 1968, respectively. In 1968, he joined the Department of Electronic Engineering, Faculty of Engineering, Tohoku University as a Research Associate. He was appointed Associate Professor at the Research Institute of Electrical Communication (RIEC), Tohoku University in 1972, and Professor of Electron Devices there in 1984. In March 2004 he retired from his appointment to become an Emeritus Professor of Tohoku University and since that time he has been continuing research and development of millimeter-wave and THz imaging technologies at RIEC. From 1990 to 1998 he was a team leader of the Photodynamics Research Center, the Institute of Physical and Chemical Research (RIKEN), Sendai, where he ran a laboratory for submillimeter wave research at the same time as he ran the laboratory at Tohoku University. He was appointed Director of the laboratory for Electronic Intelligent Systems of RIEC from 1996 to 2000, and from 2001–2004 he served as an elected member of the Council of Tohoku University. Professor Mizuno has been interested in the millimeter and submillimeter-wave (THz) region of the electromagnetic wave spectrum since 1965, and he has been continuously developing technologies for detection, generation and applications in this frequency regime. Dr. Mizuno spent a sabbatical at Queen Mary College, University of London under the sponsorship of the SRC (Science Research Council, United Kingdom) in 1973, and in 1990 spent a six-month sabbatical at the California Institute of Technology, Pasadena and Queen Mary and Westfield College, London under the sponsorship of Monbusho (Ministry of Education, Science and Culture, Japan). He is Fellow of the IEEE and of the Institute of Electronics, Information and Communication Engineers (Japan). Between 2001–2003 he served as the Chair of the IEEE MTT-S Japan Chapter. Dr. Mizuno was awarded the 17th Award of the Scientific Measurements Research Foundation in 1984, the Kenneth J. Button Medal in 1998, the Info-communication Month Award in 1999, the C-Society Symposium Award of the Institute of Electrical Engineers of Japan in 2000, the Minister Award of MEXT (Ministry of Education, Culture, Sports, Science and Technology (Japan) in 2003, and the Distinguished Educator Award of the IEEE Microwave Theory and Techniques Society in 2005. His hobbies are sailing and playing the flute, and he is the owner/skipper of a 24-foot sailing boat, which he enjoys immensely, now that he has a bit more free time!