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.

This month we travel to Japan to speak with Dr. Hiromasa Ito,[1] a longterm affiliate of the Research Institute of Electrical Communication (RIEC), Tohoku University, Sendai, and a former Team Leader in Terahertz Photonics at Japan's premier science research institution, RIKEN (Institute of Physical and Chemical Research). Professor Ito is a link in a long chain of noted THz advocates and researchers at Tohoku.

This chain began with Jun-Ichi Nishizawa[2] who according to Ito, "predicted the possibility of using the resonance of phonons and molecular vibrations to generate THz electromagnetic radiation"[3] in 1963. Nishizawa came to RIEC in 1953, and established the RIKEN Center for Advanced Photonics in Sendai, Japan, near the site of the University, in 1990. Nishizawa was also the team leader for the first major THz program in Japan (Nishizawa Teraherutu Purojekuto), which he started in 1987 at Tohoku.

The THz tradition at Tohoku continued with Professor Koji Mizuno[4], who arrived in Sendai in 1968, and became RIKEN's first THz focused Team Leader in 1990. The reigns were handed off to Hiromasa Ito in 1998, and the tradition continues under Dr. Haroaki Minamide, who took over from Ito in 2010.

In 2005, RIKEN Sendai established an entire THz research group, composed of three THz teams—Tera-Photonics, Terahertz Sensing, and Terahertz Quantum Devices. Dr. Katsumi Midorikawa, who has since been promoted to Director of the Center for Advanced Photonics, RIKEN, originally led the group. Professor Chiko Otani has now taken over as Group Leader.

Professor Ito is best known for his development of the periodically poled lithium niobate and DAST crystal-based THz sources that have done much to open up the THz gap. As you will read, however, he is also responsible for a variety of laser and nonlinear optics devices that have found application in other frequency regimes. A competent theorist, and a gifted experimentalist, Ito was forced to come up with most of his device fabrication and test equipment by building it himself. He apparently has not suffered from the experience, as there are many in the world who would like to have the products of his research.

Ito is also a strong believer in university/industry teaming and has himself volunteered to serve this cause as leader of a technology transfer initiative, director of a technology incubator program and most recently, program officer for a 10 year collaborative university/industry THz technology development effort sponsored by the Japan Science and Technology agency.

Professor Ito has spent more than 50 years as a productive and innovative researcher and has had a great influence on the direction and success of terahertz development in Japan, as well as worldwide. I hope you will enjoy his story and take away something useful from his scientific pathway to success.

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[1]I sat down with Professor Hiromasa Ito in an office of a scenically situated building—which serves as the Sendai (Japan) site for RIKEN (Institute of Physical and Chemical Research)—atop a hill overlooking the countryside, on a wonderfully sunny, but crisp, day this past Fall. This humble but steadfast supporter of THz development is part of a long line of notables at the Tohoku University and its RIEC (Research Institute of Electrical Communication) going back to the very beginnings of interest in this frequency regime in the early 1970's. When his story is added to others in this series of articles, it completes a picture that places Japan in the forefront of THz development, both then and now.

[2]Nishizawa came to RIEC at Tohoku in 1953, and stayed on the faculty until 1990. Afterwards, he became the President of Tohoku and later, of Iwate Prefectural University and Tokyo Metropolitan University. The remarks attributed to Nishizawa come from a paper he wrote (and is often cited) that appeared in *Denshi-Kagatu* (*Electron. Sci.*, vol. 14, p. 17, 1963. An interview and THz Pioneer article on Nishizawa is planned for these Transactions in spring 2015.

[3]Page 2173 from: Kazuhiro Imai, Kodo Kawase, Minamide Hiroaki, and Hiromasa Ito, "A chromatically injection-seeded terahertz-wave parametric generator," *Opt. Lett.*, vol. 27, no. 24, pp. 2173–2175, 2002.

[4]Koji Mizuno is also the subject of an article within this series: P.H. Siegel, "THz Pioneer Koji Mizuno: 50 Years in Submillimeter-Waves: From Otaku to Sensei," *IEEE Trans. THz Sci. Technol.*, vol. 3, no. 2, pp. 129–133, Mar. 2013.

Terahertz Pioneer: Hiromasa Ito

"Generating THz Energy is Crystal Clear"

Peter H. Siegel, *Fellow, IEEE*

HIROMASA ITO[1] grew up wanting to be a scientist like his father before him. The fifth of six children, he was raised in the aftermath of World War II, and like others who have been the subject of these articles, the impact of the war on Ito's life was more than an historic footnote. Ito's father, Yoji Ito[2] was a prominent member of the Japanese Navy (a Commander) and was extremely active in the development of Japan's first radar instrumentation in the early 1940's. Educated at the Technische Hochschule Dresden, Germany, under Heinrich Barkhausen,[3] Yoji worked on high power magnetrons, including the infamous Ku-Go (a microwave variation of Tesla's invisible death ray concept [1]). After the war he was severely restricted in his employment, but he managed to start a company, Koden Electronics, for the peacetime use of his Naval radio technology[4]. Koden Electronics, Tokyo, Japan, still exists today and is known for marine navigation and fish finders.

At the age of 10, Hiromasa's mentoring was left in the hands of a close friend and scientific colleague of Yoji's, Yasushi Watanabe.[5] Hiromasa's older siblings all left their small agricultural township outside Tokyo as soon as they were of age. His oldest brother went to Tohoku University to serve in Watanabe's research group. Hiromasa left home to attend an excellent Junior and Senior high school at University of Tsukuba, Otsuka, Tokyo, which specialized in science. One of the teachers there encouraged him to study English, and after graduating, he followed his oldest brother, and enrolled at Tohoku University in Sendai in 1962.

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Hiromasa was interested in atomic physics, but Watanabe recommended electronics. Ito was to make an interesting compromise. In his third year at Tohoku, he found life-long mentor and colleague, Humio Inaba, then a new faculty member at the Research Institute for Electrical Communication (RIEC) who had recently come back from a research visit at Stanford University, CA, USA, with knowledge of lasers and masers. Inaba was a physicist, but had a strong background in electronics, and was working in the Tohoku antennas group led by Hidenari Uchida. Uchida believed that radio antennas and masers would play a key role in space communications. It was due to Inaba's contributions to the Ibaraki Earth station in Takahagi, Japan that it was ready to receive the first transmission test of a transpacific satellite broadcast between the USA and Japan via Relay 1 on November 23, 1963. The transmission was planned to be an address by U.S. President John F. Kennedy, but instead was an historic broadcast containing news of Kennedy's assassination in Dallas, TX, USA, on Nov. 22, 1963.

Ito began working with Inaba on Ruby lasers and the earliest forms of laser radar (LIDAR) [2]. His Master's degree focused on mode locking [3] and other characteristics of newly invented CO_2 lasers. This included the first observation of beam spreading in liquids [4], [5]. Everything had to be fabricated and assembled locally. Ito became proficient at power electronics, glass blowing, optical polishing and coatings, crystal growth and thin film deposition.

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[1]I sat down with Professor Hiromasa Ito in an office of a scenically situated building—which serves as the Sendai (Japan) site for RIKEN (Institute of Physical and Chemical Research)—atop a hill overlooking the countryside, on a wonderfully sunny, but crisp, day this past Fall. This humble but steadfast supporter of THz development is part of a long line of notables at the Tohoku University and its RIEC (Research Institute of Electrical Communication) going back to the very beginnings of interest in this frequency regime in the early 1970's. When his story is added to others in this series of articles, it completes a picture that places Japan in the forefront of THz development, both then and now.

[2]For a short biography of Yoji Ito, see: http://en.wikipedia.org/wiki/Yoji_Ito

[3]Barkhausen was the inventor of the Barkhausen-Kurz microwave oscillator, a precursor of the klystron.

[4]Yoji developed a critically useful marine radio direction sensor as an aid to navigation. https://www.koden-electronics.co.jp/eng/about/corp-e-story.html

[5]Watanabe was a noted electrical engineer, department chair at Tohoku University and later, President of Shizuoka University. He remained a close family friend of the Itos, serving as Ceremonial Go-Between (a very honored family role) in the marriages of all 4 sons of Yoji, including Hiromasa. http://www.shmj.or.jp/english/pioneers/pnr23.html.

After completing his dissertation in 1971 and joining RIEC as a research associate, he began to become interested in optical conversion, and especially in optical parametric oscillators (OPOs). Working with Inaba, he obtained parametric fluorescence generation from 4580 to 6100 Å in lithium formate monohydrate pumped by a UV nitrogen gas laser [6]. This was followed by experimental and theoretical work on sodium formate and lithium–sodium formate crystals with high second harmonic generation efficiency (for reaching into the UV) as well as broad OPO tunability (from the optical out to far IR wavelengths) when pumped in the UV with Nd:YAG lasers [7]–[9].

In order to expand upon his nonlinear optical experiments, Ito needed to acquire the pump lasers, which were not available in Japan at the time. When Nd:YAG lasers first became commercially available in the early 1970s, his lab hosted a visit from noted Stanford Professor and laser pioneer, Robert Byer (2013 American Physical Society President), who was helping promote Nd:YAG lasers for a U.S. company. Ito became so involved, that he helped a Japanese import/export company add the laser as a product for research laboratories around the country. He also linked up with Byer, who would later (1975/1976) host him (Ito) at Stanford University, and who remained a lifelong friend and colleague.

In 1974, Ito had the first verification of phase-matched second-harmonic generation in a thin film nonlinear waveguide structure composed of ZnS deposited on lithium niobate [10]–[12]. This work led to the development of a much more efficient 4 layer structure composed of linear and nonlinear polarized materials which he managed to fabricate himself at RIEC [13], [14]. Continuing with his interests in optical waveguides and strong nonlinear crystal interactions, Ito produced an optical switch [15] and directional couplers [16] based on $LiNbO_3$, as well as an early concept for an infrared difference frequency generator based on semiconductor diode laser mixing in his nonlinear optical waveguide structures [17]. He also observed picosecond [18] and later sub-picosecond [19]–[21] pulsing with very high repetition rate in AlGaAs laser diodes, later to become an important component concept for optical communications.

In 1982, Ito moved from staff researcher to Associate Professor at Tohoku University and started working on a series of novel semiconductor laser devices. He was only able to fabricate the devices by locally assembling III-V semiconductor material MOCVD (metal–organic chemical-vapor deposition), LPE (liquid phase epitaxy), and RIE (reactive ion etch) systems [22], [23]. Ito used the III-V semiconductor fabrication equipment to invent a new type of vertical cavity surface emitting light structure that he termed the coaxial transverse junction (CTJ) laser/LED [24], [25]. He helped transition this technology, at an early stage, to the RICOH Co. laboratory in Sendai for the development of their optical heads used in print/copy machines. RICOH turned the invention into a commercial process, and is now is now using this technology quite successfully in many of their products.

Ito's sojourn into the THz domain had its origins with his work on periodically poled (domains of alternating polarization) grating structures fabricated on $LiNiO_3$ in 1988 [26]. Quasi-phase matching conditions for amplification and efficient signal beam output within the optical waveguide were realized by a poled grating deposited through a simple room temperature scanning electron beam technique [27]. Efficient second harmonic output was also obtained through a Cerenkov quasi-phase matching approach controlled by a periodic grating, where the output beam appears at a Cerenkov angle established by the grating properties [28]. These developments set the stage for a fortuitous occurrence that was to dramatically alter the direction of Ito's research.

In February 1990, a symposium was held at Tohoku by Jun-ichi Nishizawa[6], then director of RIEC, and in charge of a specially funded Japanese Science and Technology agency program on Terahertz. The theme of the symposium was "bridging the gap between light and electromagnetic waves" [29]. Nishizawa was moderating a panel discussion when he posed a question to the audience as to what techniques could best join these two dramatically disparate photonic and electronic regimes. Scanning the crowd he pointed dramatically at Hiromasa Ito, who was quietly listening from a front row seat, and asked "What do you think about this?" It was a moment of *truth* or *dare*! Ito responded rather boldly, "I believe I can use nonlinear optics to bridge the gap." *A new recruit had just entered the ranks of THz researchers in Japan*!

Two years later a young, and very determined graduate student knocked on the door. Kodo Kawase had just come from a meeting with Humio Inaba, where he had told Inaba that he wanted to work on the interaction of electromagnetic waves with biological systems for his dissertation. He was particularly excited about THz waves, because of a recent resurgence of interest in potential biological interactions originally proposed by Fröhlich [30], [31]. Inaba sent Kawase over to Ito, who when he (Ito) heard about the biological interest, and realized how difficult a topic this would be for a thesis project at RIEC, wisely suggested to Kawase that before he could explore any long wave electromagnetic interactions with tissue, he would need to have a strong and broadly tunable THz source. This argument convinced Kawase that working on sources with Ito would make a good start to his long term research goals.

THz generation through laser pumped crystals with strong nonlinear susceptibility [32], specifically lithium niobate [33], [34] had been demonstrated in the early as 1970's (see also [35]). However little improvements had been made on these systems since that time, and neither CW nor pulsed versions had been realized with sufficient efficiency and THz output power for the experiments Kawase was eager to perform. The recently demonstrated periodically poled crystalline structures Ito had been developing [36] just might prove to be the breakthrough that was required to turn these earlier demonstrations into solidly functioning instruments. So in 1992, Kawase set to work on the optically pumped THz source problem under Ito's supervision.

The first results from Kawase's and Ito's efforts to generate THz signals from their periodically poled lithium niobate structures involved difference frequency mixing in a variety of crystalline structures and appeared in 1994 [37]. Although the design was presented, there was too much THz absorption in the

[6]Nishizawa is an extremely prominent figure, and himself a pioneer in THz science. He was the leader of the Japanese Science and Technology agency's Exploratory Research for Advanced Technology Office (ERATAO) program on Terahertz between 1987–1992 and director of RIEC from 1988 to 1990. After this he became President of Tohoku University (1990–1996), President of Iwate Prefectural University (1998–2005) and President of Tokyo Metropolitan University (2005–2009). The IEEE issued an award in his honor, the Jun-ichi Nishizawa medal, in 2002. With a bit of luck we will have a Pioneer article on this notable figure in an upcoming issue of these transactions.

crystals, and the index of refraction of $LiNbO_3$ was too high at these wavelengths (> 5), to get more than a fluorescence signature. Kawase and Ito had an idea for reducing the THz absorption and output coupling mismatch by introducing a grating on top of the lithium niobate to steer the beam out of the crystal. The fabrication was tedious as the grating was introduced along the top propagation plane of the $LiNbO_3$ by using a diamond wafer saw to precisely groove the crystalline surface. The Q-switched Nd:YAG laser pump beam was directed at the ends of the crystal and the near infrared idler (allowed to exit the ends of the crystal through an appropriate antireflection coating) was resonated by a high Q external cavity. By design, the non-collinear phase matching conditions would shift the idler-to-pump propagation angle and the angle of the generated THz signal beam sufficiently such that all three wavelengths could be spatially separated. The grating further directed the THz beam so it exited the top of the crystal at a relatively steep angle compared to the pump and idler paths. For detecting the THz energy, Kawase and Ito set up both a helium cooled IR bolometer and a Schottky barrier diode detector supplied by colleague, Koji Mizuno [38], who also taught the duo useful techniques for performing submillimeter-wave measurements.

Just as the first experiments were getting underway in late 1995, Ito was recruited by the Japanese government to go on an extended trip to the U.S. and Europe as part of a program to stimulate technology transfer between government laboratories and industry partners. Kawase sent daily faxes to the hotels where Ito was staying after each day's measurements. Finally, in November of 1995 they achieved THz first light. By slightly changing the angle of the pump beam to the crystal axis (< 1 degree), the THz output could be tuned from 180 to 270 microns (1.1–1.66 THz). The output power from the grating coupler was 250 times greater than the energy that would have exited a Brewster angled edge cut in the crystal z-axis, and was in the mW range—far higher than any previous experiments. The published results appeared in April 1996 [39].

Over the next two years, Kawase, Ito, and RIEC colleagues realized higher power, broader tuning, tighter beam forming, and more compact packaging for the THz OPO [40]–[43]. The silicon prism coupler [41], an idea of Kawase's, allowed the THz beam to remain at a fixed angle relative to the crystal during frequency tuning, and enabled a fully packaged source to be assembled and eventually commercialized[7].

In 1998, Ito was appointed Team Leader for Tera Photonics at the RIKEN (Institute of Physical and Chemical Research) Photodynamics Research Center in Sendai, where he replaced Koji Mizuno. By this stage, the groundbreaking experiments on high power THz generation from $LiNbO_3$ had led to an explosion of further development, with worldwide interest in this "reborn" and greatly improved technology.

Between 1998 and 2005, the period of Ito's first appointment as a RIKEN team leader, he, in conjunction with his colleagues and staff at Tohoku, published more than 70 journal articles, and hundreds of conference papers on terahertz sources and applications, only a selected group of which have been reproduced in the references [44]–[70]. Significant milestones include: injection seeding via a yttrium fiber laser to achieve narrow line width (100 MHz) [47], [48], [52], surface-emission difference frequency mixing in a periodically poled structure [46], [55], grating tuned injection seeding to allow continuous rapidly tuned THz output without moving lenses or mirrors [56], continuous wave THz output [67], and THz generation from a two-dimensional PPLN (periodically poled lithium niobate) crystal [68]. These sources have opened up the THz bands for a wide range of applications from imaging, to spectroscopy, to the study of ultra-high field and nonlinear optical effects, and much, much more.

While improving upon lithium niobate structures, Ito was also working on new crystals with even higher nonlinearities for use as THz sources. An organic salt known as 4-N,N-dimethylamino-4'-N'-methyl-stilbazolium tosylate (DAST), invented by Tohoku's Hachiro Nakanishi [71], enabled Ito and colleagues to significantly improve the THz OPO efficiency and bandwidth [72]–[74]. DAST is still being grown at RIKEN, (I had a chance to see it up close while visiting), and although it has not yet been possible to achieve large, defect free crystals, DAST has been utilized in a wide variety of THz source and detection systems at Tohoku [75]–[81]. Since being popularized by Ito's team, especially Kawase [74], DAST is now seeing applications worldwide ([82], [83], for example).

As the PPLN OPO THz sources became more and more "user friendly" and portable, it was natural for Ito and coworkers to get involved in THz applications. Although most of these were pioneered and publicized by RIKEN Tera Photonics staff members, there were several standouts with Ito's involvement, including chemical signaturing [61], [62], near field imaging [65], [69] and imaging for a variety of commercial, medical, and security applications [66].

During all of the THz source development activities, Ito also managed to come up with an all solid-state acoustically modulated laser structure that could produce very precise continuously chirped combs—the frequency-shifted feedback laser (FSFL) [84]–[87]. This turned out to have many commercial applications including ranging [88], dispersion measurements [89], and communications [90]. It is most recently being used to perform precise 3D surface contouring at distances from 1–5 meters with accuracies in the micron range [91].

Ito retired from Tohoku University in 2007 after serving as director of RIEC for three years, but took up a second term as Team Leader at RIKEN from 2005 through to 2010. If you were under the impression that this "retirement" slowed him down, you would be dead wrong. Between 2005 and 2010 Ito plunged into THz devices and applications with a passion, publishing 40+ journal articles in the field, in addition to continued development of the frequency shifted feedback lasers, DAST and other nonlinear crystals, new low loss THz waveguide structures and new THz detectors based on pumped nonlinear crystal upconversion processes [92]–[98]. He worked most closely with Hiroaki Minamide during this period, who became the Team Leader for the RIKEN group in 2010, and is carrying on both the work of Professor Ito, as well as many new and exciting projects involving THz generators and detectors based on nonlinear optical phenomena and techniques [99], [100].

After 2010, Professor Ito shifted over to Senior Scientist at RIKEN and in his "spare time" he took on roles as Director of the Japan Science and Technology (JST) agency *Innovation Plaza Miyagi*, where he was able to work towards promoting university and industry collaborations. He then transitioned into a program officer position at JST to shepherd collaborative university research into industrial demand. Ito continues to do re-

[7]The $LiNbO_3$ source concept was incorporated into the "Goemon-R" (Phluxi, Inc., Sendai, Japan).

search, to mentor students and colleagues, and to publish copiously ([101]–[108] to list just a few), as he celebrates his 53rd year at Tohoku. The last [109], just recently published in 2014, contains a nice concise summary of the work he and his colleagues performed at RIKEN.

It must be very satisfying indeed to think back to that day in February 1990, when his very public response to Sensei Junichi Nishizawa about linking optics to electromagnetics was, "*I believe I can use nonlinear optics to bridge the gap*." Clearly, Sensei Hiromasa Ito has now fulfilled that pledge.

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The author would like to warmly thank Profs. K. Kawase and K. Mizuno for their help in setting up this interview and their kind reception in Sendai. Special thanks also go to Dr. H. Minamide, the current Team Leader of the Tera photonics group at RIKEN, for the use of his office, a wonderful tour of the RIKEN facilities, and a warm reception there.

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