Terahertz Pioneer: Tatsuo Itoh

"Transmission Lines and Antennas: Left and Right"

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PROFESSOR TATSUO ITOH[1] acquired his professional work ethic at a young age. Waking up well before dawn to help with deliveries in his father's milk business, spending the day in classes, the evening doing tutoring, and much of the time between twilight and dawn on his schoolwork, Itoh had little time for any self-indulgence. One of three boys growing up in the Yokosuka Naval district, south of Yokohama, Japan, immediately following World War II, Tatsuo remembers playing with handmade toys, especially wooden trains and paper objects he fashioned himself. His parents had graduated from teachers' colleges and had been school teachers before the war, but his father had a difficult time getting steady work in the reconstruction years. They both had strong commitments to learning and they sent Tatsuo to a Jesuit high school with the best reputation for quality teaching in the district. Eiko Gakuen[2] still exists today and is ranked in the top 10 of 4000 high schools in Japan.

Tatsuo's pre-college interests included history and gymnastics as well as math and physics. He also dabbled a bit in HAM radio, making vacuum tube receivers, and in optical astronomy. His life goal at the time was to attend Tokyo University. Getting in required passing a very tough entry exam, which he took twice, but failed both times. He blames his failure on a lack of mathematics skill—ironic considering his most important contributions to electronics were to be analytic and computational. He ended up in Yokohama National University, and perhaps fortuitously. Yokohama had no physics department, so Tatsuo chose *Jakuden*[3] or "light electronics" which translates roughly into electronics and radio science—a field that would become his lifelong career.

TATSUO ITOH

Itoh specialized in radio electronics at Yokohama and recalls a lab project to design and build a vacuum tube power amplifier. Instead of the usual triode circuit, he used a pentode controlled by the current of the second grid, which he fed through the bias circuit. The novelty of the design earned him some notability within the department. As a consequence, his adviser, who had just returned from a visit to the U.S., selected Itoh to work on the newly invented ruby laser[4] as part of his senior thesis. Itoh built the system up from scratch, including the pulsed power supply. To his credit, when he finished his thesis in 1964, he had one of the first working lasers in Japan, and his university degree.

While completing his undergraduate work, Itoh was recruited by NEC's Central Research Lab in Kawasaki, Kanagawa, Japan,

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[1]Tatsuo Itoh sat quietly with me in his office at the University of California, Los Angeles, USA, this past Valentine's Day, for this uninterrupted four-hour interview. As I pulled together his professional accomplishments, I was struck as much by his ability to tackle almost any problem in microwave engineering, as his capacity and willingness to help any student or colleague who felt the need to call on his services. The sum total of Professor Itoh's contributions, both professional and technical, are so over the top, one feels more like he represents an entire department, rather than a single individual. This short article cannot hope to cover the breadth and influence of his full career, but at least it might give the reader a sense of how much can be accomplished in a single lifetime through unrelenting focus and sacrifice.

[2]Established in 1947, Eiko Gakuen was housed in parts of the former Japanese Navy Base in Yokosuka. The school was established to fill Japan's "spiritual vacuum" (http://educationinjapan.wordpress.com/the-scoop-on-schools/a-survey-of-private-schools-in-japan-a-i/). It was later moved to Kamakura and holds about 1000 boys for a six year pre-college program.

[3]Japanese electrical engineering coursework was either *Kyoden* "heavy" or *Jakuden* "light" electricity, the former involving power and plasmas, the latter electronics and radio.

[4]The pulsed ruby laser—the first operational laser—was demonstrated by Theodore Maiman in 1960 at Hughes Research Lab, Malibu, CA, USA: T. H. Maiman, "Stimulated optical radiation in ruby," *Nature*, vol. 187, no. 4736, pp. 493–494, 1960.

where he had interned earlier characterizing phototransistors. However, instead of entering industry, he and a group of his college friends took an unusual path at the time, and they decided to all pursue advanced degrees. Yokohama had just instituted a Master's program so Itoh stayed in place, and again teamed up with his senior thesis advisor, K. Iijima [1], to work on lasers. This time he developed a composite resonator to optimize mode selection in a He–Ne laser (see, for example [2]), and then added tuning with an external mirror. During one of the summer periods, he interned at Olympus Camera where he picked up much of his exposure to commercial optics—a field which greatly influenced his later development work.

By the spring of 1966, his thesis project completed, Iijima suggested that Itoh continue his academic pursuits in America. Only one of the 20 odd universities he applied to in the U.S. was willing to accept this young Japanese student. It turned out to be University of Illinois, Urbana-Champaign. His acceptance at Illinois was due to Eikichi Yamashita, a post-doc of the renowned Raj Mittra,[5] and an early connection to THz [3] and transmission line analysis [4], who provided a very positive recommendation after reading Tatsuo's application.

Before leaving Japan, Itoh worked through the spring and summer teaching at Tamagawa University, Tokyo and earned enough money to cover his airfare to the U.S. He arrived in the fall of 1966 to what he described as a "rural desert" compared to the bustling environment of Tokyo. As a consequence, he settled into his studies with no cultural distractions. At Illinois, Itoh had a lot of course-work to catch up on, including math, physics and two additional languages (fortunately he was fairly fluent in English from the Jesuit school in Japan). He began his Ph.D. by working on the theory of confocal resonators under both Yamashita's and Mittra's supervision [5]. Taking up an idea from Illinois Professor Paul Coleman,[6] he also developed a technique for analyzing gratings with V-shaped grooves (echelette gratings [6]) using physical optics and scattering analysis. This was a time of intense work, with mid-morning coffee breaks at 10 PM not 10AM! However, Tatsuo did have time to meet his wife of now 45 years, Seiko, in an English class (she was a graduate student in sociology), and they were married in 1969, two days following the awarding of his Ph.D. degree [7].

After completing his dissertation, Itoh stayed on as a post-doc in Mittra's group for another 2 years before taking up a research appointment at Illinois. In this period he began focusing his efforts much more on transmission line analysis, which he had started during his thesis work. Between 1969 and 1976, Itoh and Mittra produced a prodigious amount of highly cited papers [8]–[29] and two book chapters [30], [31], covering strip gratings, striplines, microstrip, coupled microstrip, slot lines, dielectric guide, metal waveguides, optical waveguides, disks, periodic gratings, resonators and various flange and edge effects. Itoh also completed work on his most highly cited contribution to the microwave field, the extremely well utilized spectral domain approach for characterizing generalized transmission lines [27]–[32]. In this method, Itoh and Mittra formulate the field problem using the usual coupled integral equations approach, but then employ a Fourier transform to turn the integral solution into a series of simultaneous equations (expanded via a judicious choice of basis functions) that can be solved with matrix techniques. Eigenvalues are obtained for the propagation constants of the different modes. The approach is extremely general, and although it was first demonstrated on open microstrip lines [28], Itoh subsequently extended it to shielded lines [29] and later generalized transmission lines of all types [32].

At Illinois, Itoh also became very close with renowned antenna engineer Yuen Tze Lo[7] (Lo and Lee, *Antenna Handbook*) who was teaching electromagnetics. Professor Lo became a lifelong mentor and a companion, to whom Itoh could talk to about interests other than E&M, such as classical music and Chinese literature [33].

After several years as a research associate, Itoh was anxious to enter an academic track. However the 1970's saw the worst decline in academic employment in decades. Growth in faculty positions had slowed from 10.7% per annum in the 1960's to only 1.3% per annum by the mid 1970's [34]. Itoh saw many of his colleagues taking on extra work as taxi drivers! He applied to more than 50 institutions and despite his impressive publication record, received only one offer—at SRI (Stanford Research Institute) in Menlo Park, CA, USA. He moved there with his wife in 1976 and began work on C-band amplifiers for wireless microwave links. He quickly decided that the environment was not a good fit, and he again sent out applications for academic positions. University of Kentucky was the first place to respond positively, and Itoh left SRI in August 1977 for Lexington, KY, USA. Seiko, however remained in the San Francisco Bay Area.

At Kentucky, Itoh continued his prior analytic work and explored new directions [35]–[38]. He took up what would become an extended period as a cross-country family commuter. He was not really happy at Kentucky, however, as he found few colleagues and students he could comfortably team up with. In the meantime, his earlier application to University of Texas (UT), Austin had finally made its way through the department, and he was offered an Associate Professor slot in early 1978. He relocated to Austin in July, and there began a meteoric rise to the top of his profession.

Itoh's initial work at UT Austin was on millimeter-wave dielectric waveguide circuits [39]–[41], with support from the U.S. Army Research Office. He used a quasi-optical approach and tried to combine analysis with measurements whenever possible. He received devices (IMPATT oscillators, discrete transistors and Gunn diodes) from Fujitsu and other companies and added his own waveguide, antenna and passive millimeter-wave circuit elements. Using mainly Teflon and quartz, he demonstrated couplers, delay lines, filters, new types of waveguide and leaky wave antennas, and a whole class of millimeter-wave integrated circuit elements [42]–[57]. He also continued working

[5]Raj Mittra taught at Illinois from 1957 to 1996, and then moved to Penn State University where he is still active. Mittra is perhaps best known for his work on computational electromagnetics, but like Tatsuo Itoh, he is a prolific researcher and author with more than 700 papers and 35 books and book chapters covering a very wide variety of topics in electrical engineering.

[6]Coleman taught at Illinois from 1952 to 1988, and is well known to THz engineers for his work on harmonic generators and submillimeter-wave devices and techniques. He is an IEEE Centennial Medal winner from 1984.

[7]Y.T. Lo is best known for his work on method of moments and of course for his four volume *Antenna Handbook*, with S.W. Lee, Van Nostrand Reinhold, 1993. He taught at Illinois from 1958 through to his retirement and headed the Electromagnetics Lab from 1982 to 1990.

on his spectral domain transmission line analysis technique and applying it to many new constructs [58]–[61].

By specializing in millimeter-waves, Itoh filled an important niche at Austin. As he branched out and expanded his activities, he was very conscious of trying to establish a reputation. He chose *speed* and *novelty of approach* as his two principle mantras. Early post-docs included Lorenz Peter Schmidt (University of Erlangen), Kiyomichi Araki (Tokyo Institute of Technology) and Ikuo Awai (Yamaguchi University). By 1981 he had risen to full Professor and in 1982 he graduated his first Ph.D. student, Yi-Chi Shih [62], who later founded MMCOMM (now part of Honeywell International) and who is now trying to start a GaN foundry in China. Itoh received a chaired position at Austin in 1983.

Texas proved to be a very good place for Professor Itoh. The department gave him the freedom to pursue whatever course he thought best, and he had a continuous flow of research funding from the Joint Services Electronics Program (JSEP),[8] an extremely well endowed, quality academic research program available at a select number of universities in the U.S. During the period between 1983 and 1990, Itoh worked on a wide variety of microwave and millimeter-wave programs, which laid the groundwork for many techniques later taken up by THz designers. He contributed an amazing 11 book and book chapters [63]–[73], 89 journal papers (25 most cited: [74]–[97] and [62]) and 143 conference papers during this period! He also graduated 23 Ph.D. students, many of who have gone on to prestigious academic careers of their own. Particular results that crossed over to the higher frequency regime include his work on planar transmission lines [63], [67], [68], [80], quasi-optical analysis techniques [72] quasi-optical receiver elements [82], [86], and antennas [94], [97].

Professor Itoh's group at UT Austin typically had 15 students, at least one post-doc, and one or more visiting scientists. He emphasized practical approaches to problem solving and a combination of analysis and implementation. Appropriately, from 1982 to 1985, he took on the role of Editor of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, to which he would contribute more than 230 papers over the course of his career. He was also President-elect and President of the IEEE Microwave Theory Techniques Society from 1989 to 1990 and a participant on literally dozens of university and conference organizing committees. He contributed time to many professional organizations, including the International Scientific Radio Union (URSI), especially Commission D (Electronics and Photonics), to which he has devoted more than 35 years of service.

In 1991, Professor Itoh was enticed to leave the University of Texas and relocate at the University of California at Los Angeles (UCLA), CA, USA. He attributes his move to recruiting campaigns led by Neville Luhmann (now at UC Davis) and Nicolaos Alexopoulos (then Chair of the Electrical Engineering Department at UCLA, later Dean at UC Irvine). UCLA was particularly interested in getting involved in JSEP, and Itoh brought this association with him. There was also a personal motivation, in that his wife Seiko was still living in the Bay Area, and the move to Los Angeles was a big step in the right direction for reducing the family commuting distance.

If anything, the move to UCLA increased Itoh's work load, and he practically lived in his office. In a typical story, he readily agreed to meet with a visiting colleague who was to be in town only for a few days. Itoh told his visitor to meet him at his office at 11 PM the next evening. Puzzled, but obliging, the colleague came to UCLA at the prescribed time. Itoh arrived shortly afterwards on his way back from the airport after coming in on a long flight from Europe. They talked for three hours and then Itoh headed back to the airport for a flight to Asia early the same morning!

Above and beyond all the writing, teaching, student and staff supervision and traveling, Itoh also was asked, and agreed to assume the role of Editor-in-Chief of a new short-paper journal that had been under development within the IEEE Microwave Theory and Techniques Society for several years. Martin Schneider (Bell Laboratories millimeter-wave and optical engineer and inventor, with Eric Carlson, of the suspended substrate stripline[9]) was instrumental in pushing a new *Letters* style journal to capture the emerging field of submillimeter-wave technology. Schneider originally wanted the name *Microwaves-to-Light*[10] to specifically capture the THz regime,[11] but the journal ended up as IEEE MICROWAVE AND GUIDED WAVE LETTERS.[12] Itoh took over as Editor-in-Chief in 1990 and shepherded the new journal through its first four years (1991–1994), at which point it was publishing an average of 120 papers per year. The journal not only took a significant bite of Itoh's time, but it had a physical toll as well. Itoh was forced to divide his UCLA office in half and install a *restricted access* area in order to provide the necessary privacy protections to the submitted manuscripts and the author and reviewer correspondence—which were almost all handled via paper and snail mail!

At UCLA, Itoh focused on active antennas [99]–[104], influenced by Dave Rutledge's group at Caltech [105]–[107] for example, and on planarizing large scale antenna circuits [108]–[111], inspired by the work of Bob York at UC Santa Barbara [112], [113]. True to form, Itoh also tackled a wide

[8]The Joint Services Electronics Program (JSEP) was founded in 1946 by the U.S. Office of Naval Research, the Army Signal Corps and the Air Force. For 50 years it served as a primary funding agency for academic research in all areas of physics and electronics as well as relevant topics in mathematics and biology. JSEP centers were established at the top U.S. universities and funded countless students, faculty and staff on subjects (relevant to THz) as diverse as superconducting tunnel junctions, masers and millimeter-wave radar. The JSEP program was terminated in 1996. *Reference:* Arnold Shostak, "Anniversary of the Joint Services Electronics Program," Defense Technical Information Center, Analytic Services Inc., Arlington, VA, 139 pages, c. 1986.

[9]Martin V. Schneider and Eric R. Carlson, "Symmetrical low-loss suspended substrate stripline," U.S. Patent 04 521 755, Bell Laboratories, awarded June 4, 1985.

[10]A name Martin had communicated to the author that he was particularly fond of, but that ultimately would not stick.

[11]In fact the first issue, which only included 4 papers, did have one THz article [98]!

[12]This name too was changed in January 2001 to the current IEEE MICROWAVE AND WIRELESS COMPONENT LETTERS when Samir El-Ghazaly (one of Itoh's former graduate students) assumed the role of Editor-in-Chief. Another THz focused journal did not appear until September 2011, when this publication, IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY released its Inaugural Issue.

range of other microwave and millimeter-wave topics including superconducting circuits and devices [114]–[116], high speed photodetectors [117], new transmission line structures [118] and components [119], wireless circuits and antennas [120]–[122], and of course, dozens of analytic methods papers of which [123] is just one example.

In 1998, Itoh and his students, Bill Deal and Noriaki Kaneda, along with post-doc Y. Qian, developed a broadband planar antenna [124] derived from the 1927 Uda design [125] (Yagi-Uda), which proved to be extremely useful for high frequency integrated circuit applications. They went on to develop transitions [126], integrated active elements [127] and fully functional planar arrays [128], [129]. A variation of this antenna [130] was later integrated into the first THz MMIC circuits, developed by Bill Deal and his team at Northrop Grumman under a major government Terahertz device and circuit development program [131].

Considering Professor Itoh's mantras of speed and novelty, it is not surprising that he began to take an interest in the emerging field of photonic bandgap (PBG) engineering. Not coincidentally, he was influenced by one of the field's Pioneers, Eli Yablonovitch, who had relocated from Bell Communications Research Laboratory to UCLA's Electrical Engineering department in 1993 (Yablonovitch is now a Professor at UC Berkeley). Itoh started looking at two-dimensional PBG structures composed of various planar antenna designs, frequency selective structures, and purely magnetic surfaces [132]–[141]. He focused on microwave applications and transmission line compatible components. When Cristophe Caloz[13] arrived from École Polytechnique Fédérale de Lausanne (EPFL), Switzerland, in October 2000, a dramatic shift in emphasis was just about to take place.

In early 2000, Sheldon Schultz's group at UC San Diego demonstrated the first material with both negative permittivity and negative permeability [142]. The emerging field of metamaterials had become a practical reality [143]!

The emphasis changing breakthrough for Itoh came in 2001, when Valerie Browning at the U.S. Defense Advanced Research Projects Agency (DARPA) and Michele Anderson at the Office of Naval Research (ONR) initiated a MURI (Multidisciplinary University Research Initiative) program, PI'd out of UC Berkeley, entitled, "Scalable and Reconfigurable Metamaterials." The kick-off meeting on June 5–6, was attended by more than 40 participants from DARPA, ONR, university and industry groups. The principal investigator, Xiang Zhang at Berkeley, and co-PI's Tatsuo Itoh and Eli Yablonovitch at UCLA, John D. Joannopoulos, and Gang Chen at MIT, David Smith and Sheldon Schultz at UC San Diego, and Sir John Pendry at Imperial College, London, UK, formed the implementing teams [144].

Itoh and Caloz decided to deviate from the prevailing physics approach to metamaterials, and to develop "... an engineering approach, based on a generalized transmission line (TL) theory, with symmetric emphasis on developing practical applications..." [145]. They began with the investigation of these new *left-handed* materials in traditional waveguide configurations [146], and quickly branched out to microstrip and other transmission line structures, antennas, 2D components, slabs and prisms, lenses, surface plasmons and magnetic structures [145]–[157]. Besides their well-read text [145], Itoh and Caloz's most cited work on this subject is their review paper (with UCLA's Anthony Lai) appearing *IEEE Microwave Magazine* in 2004 [158].

[13]Christophe Caloz is a well-known figure in the Metamaterials community and is now a Professor at École Polytechnique of Montréal, Canada.

During this period, where the focus was on *Left-handed transmission line structures*, Itoh did not falter on his other research areas. He continued to publish book chapters and papers on wireless applications [159], [160], new types of passive antennas [161], active antennas [162], [163], dielectric media [164] and even microwave engineering education [165]. After 2004, Itoh continued to develop and apply his CRLH (composite right and left handed) analysis techniques to a wide variety of problems [166] including leaky wave and resonant antennas [167]–[171], transmission line and waveguide metamaterial components [172]–[174], filters [175]–[177] and other microwave circuits [178].

Most recently, Prof. Itoh has focused his attention on applications of metamaterials to THz quantum cascade lasers [179]–[182], for which he won, along with Philip Hon, Amir Tavallaee, Q. S. Chen, and Ben Williams, the 2012 Best Paper award from this journal [183]. He continues to apply his considerable analytic skills to problems in transmission lines and antennas *left and right* [184]–[189], and to project metamaterial application into the future [190].

Prof. Itoh is still teaching 3 classes, attending at least a half dozen meetings and conferences, and publishing more in one year than most of us will in 10. He also sets aside at least an hour each day to respond to the daily requests of hundreds of colleagues. At the end of our chat, Prof. Itoh waxed a bit nostalgic, and suggested that he would like to learn an instrument or to take up a hobby, but he is really hoping for one more hot area to come along to attract his attention. One can only wonder how he will find the time!

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