MTT Special Issue Guest Editorial

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I. Introduction

THIS SPECIAL Issue of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES is focused on the microwave and millimeter wave applications of high temperature superconductivity (HTS) with an emphasis on the Naval Research Laboratory's program known as the high temperature superconductivity space experiment (HTSSE). High temperature superconductivity was discovered in 1986 and superconducting materials with transition temperatures in excess of 77 K, the boiling point of liquid nitrogen at atmospheric pressure, were discovered in the spring of 1987. Just four years after this latter discovery, there was a Special Issue of the TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (vol. 39, no. 9, September 1991) entitled "Microwave Applications of Superconductivity." In that issue, there were 17 papers describing relatively simple HTS microwave devices, such as filters and resonators, antennas, HTS materials, and simulation and modeling of HTS microwave devices. This current Special Issue, appearing five years later and just nine years after the discovery of materials with superconducting transition temperatures above 77 K, contains a total of 21 articles. There are ten invited papers describing complex and sophisticated HTS advanced microwave devices and subsystems which were designed and built to specifications, interfaced with cryogenic refrigerators and integrated into a satellite payload which will be launched in 1997. The remaining 11 contributed articles describe additional novel and sometimes very sophisticated microwave applications of HTS technology which were developed in laboratories throughout the world. The level of complexity of these HTS components, sometimes integrated with semiconductor components, and the attempts to insert HTS microwave technology into systems, both space-based as well as terrestrial, is amazing considering that a little over ten years ago speculating about high performance superconducting microwave components operating at temperatures near that of liquid nitrogen would have been considered suitable script material for Star Trek.

It is generally agreed on by members of the microwave superconductivity community that the Naval Research Laboratory program known as the high temperature superconductivity space experiment (HTSSE) was a major catalyst to the development of this technology. Shortly after the published account of the discovery of superconductivity in the compound yttrium-barium-copper-oxide (YBCO) at temperatures near 90 K, scientists and engineers at NRL became interested in the prospects of employing high temperature superconducting electronic devices and subsystems in operational remote sensing and communication systems. Such devices could be operated using only liquid nitrogen, or, possibly, physically small, closed-cycle cryogenic refrigeration systems. These coolers have orders of magnitude smaller weight, volume and electrical input power requirements than those for the better known "low temperature superconducting" materials which must be operated below 20 K.

The very low attenuation, wide bandwidth, low noise and high speed associated with high frequency superconductivity are very attractive attributes for high performance communications and remote sensing systems. The engineers in the NRL Naval Center for Space Technology (NCST) quickly realized that these properties of superconductivity were nearly ideal for their system requirements. Additionally, the reduced cryogenic burden for their deployment in space might be acceptable considering the improved performance that could be realized from the use of this "ultimate" electronic technology. In December 1988, the HTSSE program was approved by the Navy with funding from the Space Technology Program Office of the U.S. Navy Space and Naval Warfare Systems Command (SPAWAR). From the very beginning this program was designed to be *very focused*, with *definite goals* and *objectives, specific deliverables*, and *periodic space flights* to demonstrate the space-worthiness of this new technology. One of the goals of this program was to accelerate the development of HTS into a viable electronic technology and to focus this technology toward potential space applications. The HTSSE program was definitely a *development* program to produce devices and components, not a *research* program to search for new materials or to understand the basic phenomena responsible for superconductivity at these (relatively) elevated temperatures. A broad agency announcement (BAA) published in January 1989, which was the first public announcement of this program, clearly stated these goals.

II. HTSSE-I Program

The HTSSE program consisted of three phases. The first phase, which became known as HTSSE-I, focused on simple HTS electronic devices. The second, HTSSE-II, addressed, complex HTS devices and subsystems. HTSSE-III was to have been a complete operational system with HTS components performing crucial functions so as to enhance the performance of the candidate systems. When the contracts were awarded in June 1989 for the HTSSE-I deliverables, each successful

Manuscript received March 11, 1996.
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Publisher Item Identifier S 0018-9480(96)04783-7.

provider agreed to supply to NRL five devices of nominally "identical" electrical performance, each in a package that would be space qualified. Each provider had 12 months to complete their devices. Thus, only three years after the discovery of these materials, physically and electrically robust HTS components—five each—had to be delivered for space qualification and integration onto a specially designed and built satellite payload. This was a significant challenge considering the lack of maturity of this technology at that time.

To achieve the goals of HTSSE-I, the device providers had to accomplish the following very challenging tasks:

1) Stabilize a thin or thick film or bulk HTS materials fabrication technology so that they could produce at least five copies of the desired device;
2) design and fabricate the devices of interest;
3) make careful electrical measurements at cryogenic temperature (this was especially challenging for microwave devices where the network analyzer used to measure these devices had to be properly calibrated for use at cryogenic temperatures);
4) mount the device in a box or structure with standard connectors and make mechanically strong contacts between the standard connectors and the HTS device;
5) subject the packaged device to the shock and vibration required for electronic components designed for satellite use.

These were very serious challenges. Not only was the technology relatively immature but most of the researchers interested in superconductivity had never addressed the issues associated with packaging electronic devices for space. Despite these technological obstacles, more than 45 proposals were received from industrial, government, and academic laboratories. Some were proposals in response to the BAA; others were offers of devices whose development was funded by other U.S. or foreign agencies. After careful review, the HTSSE team selected 23 devices for inclusion in the program. Of these, 19 were thin film microwave devices (e.g., resonators, filters, delay lines, couplers, and antennas) and two thick film or bulk devices (e.g., cavity resonators). The remaining two were an infrared bolometer array and high current capacity electrical leads.

During the one-year development period for the HTSSE-I devices, more than 20 research and development organizations had very concentrated efforts to perfect this technology. NRL provided about one-person-year of financial support but, in most instances, the research organization invested many times that effort (either funded internally or by other sources) to develop these devices. Hence, during the 1990–1991 time frame, microwave applications were the major thrust driving the HTS device community, possibly rivaled only by the interest in superconducting quantum interference device (SQUID) magnetometry.

Of the 23 devices developed for HTSSE-I, 18 were delivered to NRL for electrical verification and space qualification. All of these were microwave devices. While the devices were under test, the engineers in the NCST at NRL designed and fabricated a satellite payload for these HTS devices which contained a cryogenic refrigerator and spacecraft ambient temperature measurement electronics and would be integrated onto a host DOD satellite. The electronic measurement system was a fully space-qualified scalar network analyzer. Once the satellite was launched and on orbit, the devices would be cooled by the cryogenic refrigerator to operating temperatures (77 K). Then, on command from the ground, a sequence of measurements would be initiated to measure the microwave parameters of the HTS devices. The data collected would be downlinked to a ground station, where the data could be analyzed to detect changes, if any, due to the space environment. The planned mission duration was about one year.

The HTSSE-I payload was completed in late 1992 and manifested on a U.S. Air Force satellite launch scheduled for 1993. Unfortunately, the payload did not achieve orbit and the HTSSE-I experiment was lost. Despite the unfortunate loss of on-orbit data from the HTSSE-I experiment, the program did conclusively demonstrate that viable and robust HTS microwave devices could be fabricated, packaged, and space qualified. The performance of the HTS devices demonstrated superior electrical performance compared to competing technologies with the same weight and volume or their performance was comparable to conventional technologies with at least an order of magnitude reduction in weight and volume. The demonstration in 1992, just five years after its discovery, that high temperature superconductivity was a viable and robust technology which could be qualified for space deployment was a major milestone in the development of HTS electronics.

III. HTSSE-II Program

In the 1991–1992 timeframe while the HTSSE-I payload was under construction and test, a solicitation for proposals was issued for HTSSE-II which focused on advanced HTS devices and subsystems. In HTSSE-I, any device that performed a useful spacecraft electronic function was accepted. In this second phase, the prospective provider had to design and, then, fabricate to this design an HTS component which performed a significant function in a typical spacecraft payload. An example is a four-channel multiplexer with a specific center frequency for each channel, bandwidths, and band-edge roll-off characteristics. Other proposed deliverables consisted of HTS components integrated with semiconductor devices, the latter operating either at the same temperature as the HTS components, or, possibly, operating at spacecraft ambient temperature. Some of the proposed components were digital circuits, which at that time had not yet been demonstrated. If successful, the very low power and high speed potential of these digital circuits could have a major impact on future spacecraft systems. These proposals were clearly the next major step in the development of HTS technology for spacecraft deployment. In Spring 1992, a total of 13 deliverables was selected from more than 30 proposals received in response to the NRL solicitations. These development programs were funded, either under direct NRL contracts, by other government agencies, or by foreign governments. Again, as in the case of HTSSE-I, the funds provided by NRL under the HTSSE contracts were very heavily leveraged by internal R&D funds, or by funding from other U.S. or foreign government's agencies. The HTSSE program continued in a major leadership role in expediting the development of HTS microwave technology.

The first invited article in this Special Issue contains a list of the 13 HTS advanced devices and subsystems selected for development by the HTSSE-II program as well as a description of the common cryogenic cold bus where seven of the eight HTSSE-II components selected to be flown are mounted. The eighth device is a stand-alone subsystem where the HTS device is integrated with its own cryogenic refrigerator. After integration with their refrigerators into thermally efficient cryogenic packages, they were mounted onto the HTSSE-II satellite deck along with several spacecraft ambient temperature electronic packages (amplifiers, multiplexers, receivers, analog-to-digital converters, etc.). The entire HTSSE-II payload was tested for electrical functionality and for space qualification. The HTSSE-II payload and its HTS components have functioned exceedingly well except for a few minor problems with two of the subsystems. The payload is to be shipped to Rockwell International in Spring 1996 for integration onto the advanced research and global observation satellite (ARGOS) for a scheduled launch in Spring 1997.

IV. Lessons Learned

As the payload for HTSSE II was going through spacecraft acceptance testing prior to shipment to Rockwell, the NRL team who managed the two completed phases of the HTSSE program, concluded that they had established a unique paradigm for developing a new technology. They also have a set of "lessons learned" which might be helpful to other organizations who are attempting to develop new technologies. Hopefully, these lessons, based on experiences with high temperature superconductivity, are universal and will be useful in developing other technologies. They are:

1) *Provide a challenging time schedule with intermediate goals and objectives and, if appropriate, periodic deliverables to verify the maturing of the technology.* By structuring the HTSSE program in phases with each phase having deliverables, an impartial evaluator could observe significant advancements since the previous goal. By requiring deliverables during the program, the community had to address issues such as packaging and integration with conventional electronics and, thus, demonstrate that the technology is indeed robust and viable.
2) *Offer an attractive final goal.* A final goal is very helpful to focus attention of the development team on the long-term activity. Although intermediate goals and milestones are important, it is extremely critical to focus on the final goal. In the HTSSE program, the goal was a satellite launch. For a commercial activity, the final goal might be a final prototype or preproduction package ready for marketing.
3) *Encourage free exchange of information among team members and among the several contractors working on the program.* Information is a vital ingredient to any program. Each of the participants has different experiences and expertise which should be made available to all the other participants. For example, in the HTSSE-I program, we had three reviews, a kick-off meeting, a mid-year and a final review, at which all 23 participating organizations presented their successes as well as failures in a very open and "no-holds-barred" manner. Thus, each participant was able to learn from their colleagues what worked and what did not work, and did not have to repeat failures.
4) *Minimize paperwork and formal reviews.* It is the responsibility of the program management to know the goals and milestones, which projects are on schedule and which are falling behind, and which performers are making progress and which are marginal. This can be done by frequent (but not too frequent) visits to the participating organizations for *informal* progress reviews and, most importantly, for discussions with the workers in a casual environment, for example, over coffee or a soft drink. Formal presentations consume time and resources to prepare complex, multicolored visual materials which can easily disguise or mask deficiencies in the program. In an informal meeting in the laboratory or over a cup of coffee, the true situation and status usually will be evident. This is a much better means for maintaining awareness of progress in any program as well as establishing good rapport with the participants.
5) *If the development program is funded by the government, leveraging other government programs and industrial R&D programs is essential.* In any new program, funding is always scarce; and if one can leverage other government or industrial-supported R&D activities, a much stronger program will develop. In the cases of HTSSE-I and II, we estimate that the program was able to leverage, by a factor of two to three, its own funding when the participants had other funding sources which could be applied to this program.
6) *Use an impartial laboratory, such as a government in-house laboratory, with the relevant expertise and experience to coordinate the program and to verify performance of the deliverables.* It is extremely important to have the program managed by a competent and impartial organization, who has no vested financial interest in the outcome of the program. For the HTSSE program, NRL was a logical and qualified candidate for managing the program. NRL's Naval Center for Space Technology has built more than 80 satellites in the previous 30 years and NRL has a large group specializing in radiation effects on structural and electronic materials in the space environment. Furthermore, NRL has a strong research team experienced in superconducting materials and electronics. Thus, NRL could be and was an impartial judge to exercise the choice of devices and components and to evaluate the eventual results of the program without fear of jeopardizing the long term interests and goals of the organizations.

V. Conclusion and Future Directions for the Technology

The unique properties of the superconducting state can provide both military and civilian communities with the "ultimate" electronic technology possessing low insertion loss, wide bandwidth, low noise and high speed. The engineers and scientists at the Naval Research Laboratory realized shortly after the discovery of high temperature superconductivity that this newly discovered phenomenon could significantly impact future generations of space-based communications and remote sensing systems. A program (HTSSE) was initiated to focus the attention of the superconductivity community on space applications of this technology and to demonstrate that this was a viable and robust technology that would survive space deployment. During the initial phase of the HTSSE program, a unique government, industry and academic partnership was organized to provide HTS microwave devices which were space qualified. Even at that very early stage of development, this technology was viable and robust and could be configured into practical electronic components.

Starting in 1992, the second phase of the HTSSE program focused on the demonstration of advanced microwave devices and subsystems. These were either complex HTS components, such as multiplexers, or subsystems with HTS devices integrated with semiconductor devices operating either at the same cryogenic temperature as the HTS components, or, possibly, at spacecraft ambient temperatures. HTSSE demonstrated that a low-cost, reliable cryogenic space test bed for state-of-the-art HTS components and subsystems can be built and space qualified and integrated onto a satellite. HTSSE also showed that state-of-the art cryogenic refrigeration systems can be integrated into space systems either to cool a major portion of the spacecraft or for localized cooling of an individual device or subsystem.

During the evolution of the HTSSE-II phase, the HTS community remained focused on microwave applications. Concurrently, commercial activity started which is attempting to insert HTS microwave technology into wireless communications base stations. This activity was started after the viability and robustness of HTS microwave devices had been demonstrated in the HTSSE-I phase. This commercial interest is a spin off as much of the technology developed for the HTSSE program can be transitioned. As both applications of HTS microwave technology mature, one will benefit from the successes of the other.

In the original formulation of the HTSSE program, there was a third phase, usually designated HTSSE-III, which was to have been the development and space qualification of a complete space communications or remote sensing system whose performance would have been significantly enhanced by the use of HTS technology. Although HTSSE-I and II were successful in demonstrating the enhanced performance and robustness of HTS microwave components and subsystems, before starting a program to develop an entire spacecraft system based on superconductivity, NRL and several other government laboratories have undertaken detailed trade-off studies to quantify and document the advantages that would result from the insertion of this technology into various candidate operational systems. These studies were on-going at the time this guest editorial was written. Based on these and similar assessments, decisions about inserting high temperature superconductivity electronic components and subsystems into space systems, and, in addition, into terrestrial systems, will be made.

HTS technology will only be introduced into military or commercial systems when the end user can be overwhelmingly convinced that this is the only technology that can provide a significant and desired advantage at a system level over what can be obtained using more conventional technologies.

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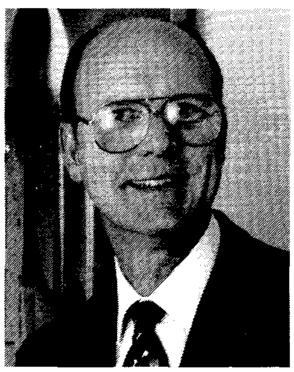
Dr. Nisenoff is a member of the American Physical Society. He is a member of the Board of Directors of the Applied Superconductivity Conference, a member of the Organizing Committee of the International Cryocooler Conference, and a member of the Advisory Board of the journal *Cryogenics*. In MTT, he is Chairman of Technical Committee 18-Superconducting Technology, and a member of the Technical Program Committee of the MTT-S Symposium.



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From 1969 until 1990 he was on active duty with the U.S. Navy as a Cryptologic Officer. After completing Officer Candidate School, he was initially assigned as a Research Physicist to the Materials Research Branch, National Security Agency, and conducted R&D in high density, electron beam addressable, memory storage devices using vanadium oxide thin films and scanning electron microscope. Subsequent assignments over the next 12 years involved shore-based operational field sites and at-sea duties involving radio wave propagation studies, signal processing, geolocation, specific emitter identification techniques, and cryptologic support operations at tactical, theater, and national command levels. In 1984, he was assigned as Officer-in-Charge of the Navy's Sugar Grove, WV facility which supported R&D in various space programs, cryptologic exploitation techniques, and geolocation algorithm development. From 1987 to 1990 he was assigned to Space and Naval Warfare Systems Command Space Technology Office, located at the Naval Research Laboratory (NRL) in Washington, DC, and served as Technical Division Director, responsible for all R&D initiated by that office. Areas of R&D included: MIC/MMIC devices, vacuum microelectronics, signal analysis and processing techniques, advanced power systems, high efficiency solar cells, high temperature superconductivity, and space cryogenic systems. He was the Sponsor's Program Manager for the high temperature superconductivity space experiment (HTSSE). In 1990, after retirement from active duty at the rank of Commander, he joined AlliedSignal Technical Services Corp. (ATSC) as a Senior Scientist. His current activities involve supporting NRL's Advanced Systems Technology Branch, Naval Center for Space Technology, concerning evaluation and use of advanced technologies and their applicability to space systems. In addition to serving as ATSC's Project Manager for HTSSE, he is involved in other technology developments including: maritime remote sensing, MMIC subsystems for modular payloads, focal plane array electronics, positioning and tracking via GPS, single emitter identification, signal analysis, and exploitation techniques.

Mr. Meyers is a member of the American Physical Society (APS), American Institute of Aeronautics and Astronautics (AIAA), Armed Forces Communications and Electronics Association (AFCEA), and Institute of Electrical and Electronics Engineers (IEEE). He has been Guest Lecturer at Florida State University, Michigan Technological University, Air Force Institute of Technology, and the U.S. Naval Academy on the topics of HTSSE and development of advanced technologies for space systems.