

HIGHLY COMPACT & EFFICIENT JTRS RADIOS USING SUPERCONDUCTOR MICROELECTRONICS – A QUANTUM LEAP IN PERFORMANCE: THE CRYOPACKAGE

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ABSTRACT

Superconductor MicroElectronics (SME) are rapidly redefining the state-of-the-art in wireless RF performance. SME-based Digital RF subsystems, enabled by compact cryocoolers, have the potential to **achieve all JTRS OBJECTIVE requirements (not just the thresholds) for performance, SWaP, and Cost as an Independent Variable (CAIV) targets for Clusters 1, 3 and 4.** Compact cryo-packaging is the key to deploying SME-based digital RF subsystems in JTRS and other wireless radio systems. A compact cryocooler provides the cryogenic environment for the superconductor Multi-chip Modules (MCMs). The cryo-package (comprising the MCM and compact cryocooler) includes the mechanical and electrical interfaces to the JTRS radio. For example, **a single SME-based Digital RF subsystem provides a 10-channel full-duplex transceiver in less than 500 in³, 30 lbs, and 150 watts; and an availability (up time) on the order of 99.998%.** This paper discusses all aspects of cryo-packaging, which include compact closed-cycle refrigerators or cryocoolers, methods of building and cooling superconductor multi-chip modules, managing thermal loads of input-output leads between warm ambient temperature electronics and cold superconductor electronics, and electromagnetic shielding.

1. INTRODUCTION

The huge leap in performance obtained with Superconductor MicroElectronics (SME) is due to fundamental physical properties of superconductors. These properties lead to unprecedented integrated circuit performance, and digitization of high bandwidth analog signals with quantum accuracy [1]. The SME circuits must be appropriately packaged to yield reliable products serving the increasing demand for ultra-high performance and exceptionally cost-effective communication systems, including both wireless and optical networks, and spanning the full spectrum of commercial, military, and space markets. The key SME enabler is the cryogenic environment that provides the required superconductor working temperature and, as a corollary benefit, ultra-low thermal noise. The key elements for successful cryopackaging consist of the following:

- Provision of a compact, efficient, and reliable cryocooler to provide the “temperature bus” (equivalent to power bus in semiconductors).
- Multi-chip module packaging of the SME integrated circuit to allow for efficient known-good-die (KGD) screening, higher yield, and more complex operations.
- Thermal management, consisting of the optimization of the heat load onto the cryocooler while maintaining good signal transmission to the circuits. This reduces the power requirement of the cryocooler, leading to further Size, Weight, and Power (SWaP) savings.
- EMI and thermal radiation shielding, which are an integral part of the package, and serve to further reduce the thermal load (leading to better power efficiency) as well as to shield the SME circuits, whose inherent sensitivity is key to the high performance, from ambient DC as well as AC electromagnetic fields.

2. CRYOCOOLERS

The key element in the cryopackaging is the cryocooler – a cryogenic refrigerator needed to maintain the SME circuits at the low temperatures required for their operation. The technology for producing these cryocoolers has evolved over several decades, and recent developments have now enabled robust products with exceptional efficiency and reliability [2]. Products utilizing superconductor materials for analog signal processing are already commercially deployed. Over 3000 units have demonstrated more than 11 Million hours of operation with mean-time-between-failures (MTBF) exceeding 800,000 hours or over 90 years! At the same time, the technology and product development roadmap is established for the timely production of cryocoolers intended for packaging of SME circuits. Appropriate cryocoolers serving the varying requirements of civilian, military, and space markets have been defined with a number of technology and manufacturer options available.

Cryocoolers are essentially refrigerators, where the term “Cryo” refers to reaching a temperature range typically below 100 Kelvin (K), and in the HYPRES SME case, around 5 K. In the superconducting electronics context, the cryocooler provide “thermal conditioning” of the circuits, much like other thermal conditioning methods (fans or

passive coolers, etc.) are used for other electronics technologies. However, unlike conventional electronics, the cooling is not used to “get the heat out”; it is used to get the superconductive effect.

Cryocoolers are the enabling package for SME and determine the overall size weight and power of the SME-based system. It can be viewed as the “power supply”. This “power supply” not only provides the very small amount of required electrical power (~mW per chip) but also provides cooling - providing a “cold bus” to which the SME Integrated Circuits (ICs) must be thermally anchored. Several cryocooler designs, employing different thermodynamic cycles, are available from multiple, well-established vendors. Remarkably, the technology witnessed dramatic advances with the advent of the semiconductor industry where commercial cryocoolers were developed to serve as fundamental elements in the high volume fabrication facilities producing semiconductor integrated circuits. Virtually every vacuum system in these facilities is equipped with an ultra-highly reliable cryopump. The economics of this market have driven cryocooler technology and products to ever increasing reliability and low cost. Infrared detection in military applications are enabled by cryogenic cooling, as are critical scientific experiments involving both space-based as well as ground based electronic instrumentation [3]. Innovative mine-detection and submarine-detection systems are built and tested using cryocooled superconducting devices and magnets.

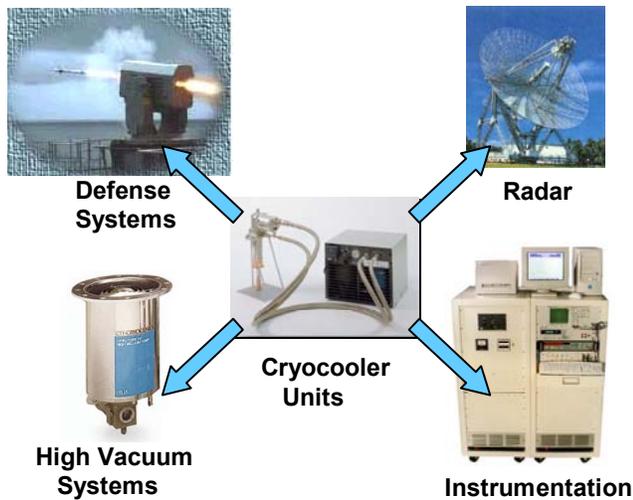


Figure 1. Cryocoolers are successfully deployed in many differentsystems serving a variety of applications and platforms.

Cryocoolers intended for space applications are specifically and successfully designed for maintenance-free operation, and typically last beyond 10 years after missions are ended. In fact, the semiconductor-based processing electronics that succeed the cooler often are triply redundant in an attempt to match the reliability of the cryocooler, which has never failed. Cryocooler technology and products have met all

market and application demands in performance, reliability, and cost. Figure 1 illustrates the multiple, successful, deployments of systems incorporating cryocoolers.

Cryocoolers are deployed in military systems ranging from missiles, to tanks, rotary aircraft, to soldier helmets, where they perform functions of imaging, night vision, and target seeking through infrared detections. Cryocoolers have proven their battle-readiness and their key contributions to military competitiveness.

An example of a field use of cryocoolers coupled with superconductor electronics is in high quality filters for the wireless communications market. These high quality analog filters enhance the range of wireless base stations while simultaneously reducing interference. Within the past five years, cryocoolers were successfully developed to meet the packaging requirements of these products [4]. Three companies in the US have already deployed over 3000 such filters in wireless base stations nationwide. More companies exist world-wide. The cryocooler in the product is transparent to the user, and the package is usually a rack-mountable electronics “box” that is easily connected and continuously and remotely monitored. These products are rapidly gaining acceptance among cellular service providers, with volume sales to major customers in the US and Europe underway. Examples are shown in Figures 2 and 3 below.



Figure 2. Cryocoolers were efficiently developed to meet the performance and market needs of superconducting analog filters, including, in particular, rugged tower-mount models. (Shown here both from Superconductor Technologies, Inc., and from DuPont Radio Technologies)



Figure 3. Several manufacturers currently use different cryocoolers to serve the wireless communications market. Shown in order are product offerings from Superconductor Technologies, Inc (2 left packages), and ISCO International, Inc. (right).

The reliability of these cryocoolers deployed in wireless communications base stations has been remarkable. The total number of run-hours has been steadily increasing as more units are deployed, and with this increase, the

reliability figures as measured by mean-time-between failures has also increased. Recent figures demonstrate MTBFs of over 800,000 hours or over 90 years. This translates into impressive uptime estimates of 99.998%. This includes the effect of both the cryocooler and the outside electronics, with many of the early failures due to the semiconductor-based control electronics!

Cryocoolers for these superconductor applications have followed a typical development phase with early generations emphasizing margins and performance at somewhat larger size and weight, and rapidly producing next generations products with successive compactness and miniaturization to lead to the current compact and rugged product profiles. A similar path had been proven earlier with cryocoolers for infrared detection and imaging systems. The same path will be followed for cryocoolers for SME. HYPRES has defined the requirements for these cryocoolers, and conferred with all the major cryocooler developers and manufacturers. The deliberations to-date along with responses to a request-for-information have evolved into a well defined roadmap and a detailed specification for this product. The evolution in SWaP, already underway, is illustrated in Figure 4.

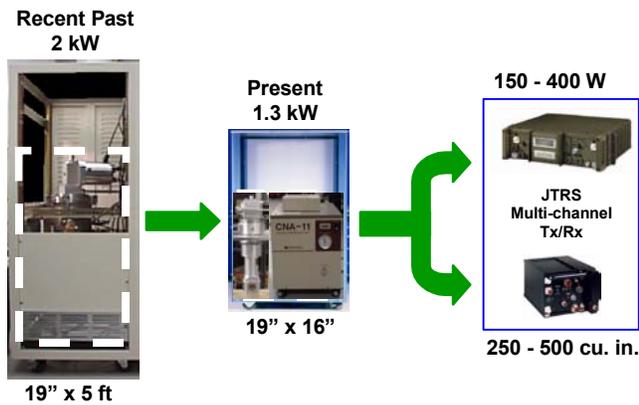


Figure 4. The roadmap is defined for the development and productization of cryocoolers integrated with mixed signal superconducting electronics. A number of viable approaches have been identified, along with a number of potential suppliers, including second-sourcing capability.

A number of viable approaches have been identified, ranging from traditional implementations, such as "Gifford-McMahon," "Stirling," "Joule-Thompson," and "pulse-tube," to innovative methods based on miniature micro-electromechanical (MEMS) device technology implementing miniature turbines. The multiple solutions and sources available add to the confidence that cryocooler developments shall meet the market demands in high performance digital and mixed signal communications across all segments: commercial, military, and space. It is important to note that these developments involve no fundamental science issues to address. Rather, the key to

the solution is effective engineering and manufacturing, and, for the larger commercial market, economies of scale.

3. MULTI-CHIP MODULES

Once a cryocooler is integrated into the system, additional circuits and functions can be added with little or no increase in the heat load requirement, and therefore the SWaP factor. As a result, the efficiency of SME is significantly enhanced by incorporating more total system functions within the cryogenic environment. This is readily achieved by the use of multi-chip modules (MCMs). An added benefit of MCMs is the improved yield efficiency realized by breakdown the circuits into smaller ICs, thereby achieving a faster identification of known-good-dies (KGDs). The use of thermally conductive silicon substrates enables uniform distribution of the heat load, and temperature stabilization.

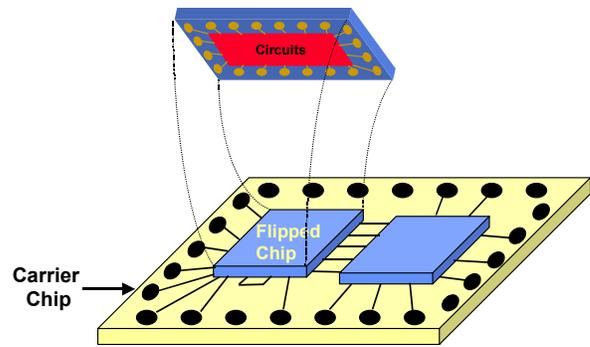


Figure 5. Multi-chip modules (MCMs) enable complex functions and improved efficiency and yield

The MCM consists of a carrier with passive transmission lines, onto which a number of active SME circuits are flip-chip bump-bonded. This arrangement ensures small size and close proximity of the interconnections, thereby minimizing loss and dispersion, and preserving the integrity of the high speed signal transmission. This integrity is a necessary condition for the success of the MCM approach to achieving complex operations from a collection of SME circuits. The technology for achieving the required high speed transmission has been successfully demonstrated at HYPRES. The specific challenges that were addressed included the high speed transmission of single-flux-quantum (SFQ) pulses between chips via the carrier MCM, interchip clock synchronization, and the generation and distribution of a stable low-jitter clock. Data transfer through MCM carriers were demonstrated up to 20 GHz.

4. THERMAL MANAGEMENT

The most direct impact on the SWaP of SME-based systems derives from the optimization of the heat load on the cold stage of the cryocooler. Minimizing the so-called "heat lift"

requirement implies easing the performance requirement of the cryocooler, and thereby reducing the SWaP. This is illustrated in the following diagram.

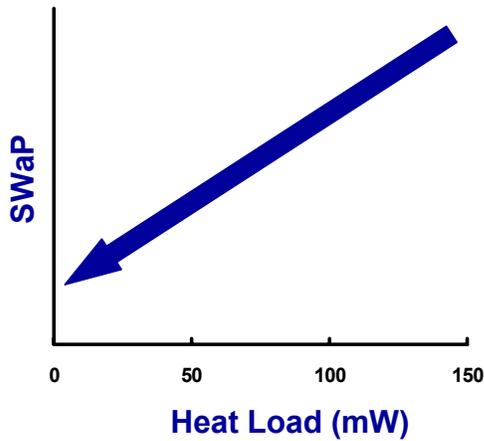


Figure 6. Minimizing the heat lift requirement of the cryocooler, determined primarily by the I/O leads, is the most important factor in reducing the SWaP requirements.

It is important to note that, in the absence of heat conduction through the input-output (I/O) leads connecting the SME chips to room temperature interface circuits, the intrinsic heat dissipation is minimal. Therefore, a major factor in minimizing the heat lift is the optimization of the I/O leads to provide the least thermal conduction while maintaining adequate electrical and bandwidth properties. Other factors also come into play, including thermal radiation loading. Multiple “tools” are available to make this cryopackaging optimization successful. A variety of electrical connection approaches, from coaxial cables to optical fibers to microstrips enable us the flexibility to make adaptable choices. Special chip mounting techniques lead to robust signal transmissions at high frequencies. These include the use of different materials, architectural changes involving multiplexing and bias current recycling, as well as radiation heat load reduction by the use of standard cryogenic packaging techniques.

Thermal power budget analysis is conducted to inventory all the contributions to the heat lift, which in turn determines the SWaP of the cryocooler and of the system. An example of such a calculation is shown below for a 10-chip Digital RF Transceiver system. On-chip heat dissipation is very low, about 1.2mW/chip, and the main contribution is typically from the heat transmission through the electrical connections. Improvements are possible by using different materials for the I/O connections, by using modified architectures for recycling the bias currents, and by optimizing the radiation heat load. Significant reduction in the heat lift is obtained by using special lines for the high speed I/O lines. Over 50% improvement is realized, leading to significant margins in SWaP for JTRS. Further

optimization is obtained through architectural improvements using multiplexing and current recycling as well as through reduction in the radiation heat load. An additional ~ 45% improvement is obtained, which allows ready transition to a significantly smaller cryocooler package.

Source of Heat	Heat per Line (mW)	Number of Lines	Total load from source (mW)
On chip power dissipation (10 chips)	N/A	N/A	12
DC Current Bias Line	0.04	20	0.8
DC Voltage Monitors (thin phosphor bronze)	Low	20	0.2
20 GHz Clock [ON-CHIP]	0	0	0
Digital Output and Monitor Lines 1 GHz	0.15	80	12
Analog Input Signal	0.8	10	8
Thermal Radiation from 300K and 60K sources			< 15
Total			< 48 mW

Figure 7. Thermal Requirements for SME JTRS Transceiver Matches with Compact Cryocooler

5. MECHANICAL MOUNT AND SHIELDING

The sensitivity and high dynamic range afforded by SME requires that only the intended signal reach the circuits and that adequate EMI shielding be implemented as part of the mechanical packaging. In addition, SME circuits respond to dc magnetic fields, which requires the use of high permeability material (usually mu-metal) in the shields. Materials and techniques for this packaging are established and readily implemented. Furthermore, advanced mechanical contact techniques allow for effective high speed signal transmission from the input cables to the chips while maintaining excellent thermal contact with the cold link as well as resilience, vibration-tolerance, and flexibility. An example is shown in the following figure, with custom techniques proven to successfully transmit signals up to 40 GHz. The flexible contacts are resilient to vibration including that of the entire platform (for example, in HMMWV, tanks, aircrafts, etc.).

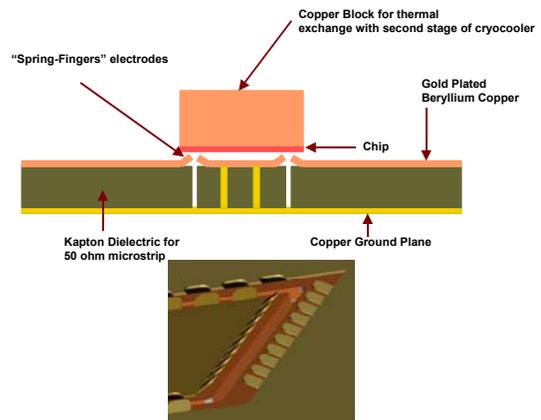


Figure 8. Vibration-tolerant chip mount

6. CONCLUSIONS

The constraints of cryocooling SME have been traditionally viewed as a major impediment to its applicability. The recent advances in cryocooling technologies, coupled with the proven performance capability of novel thermodynamic cycles and cryopackaging approaches, have definitively altered this paradigm. The roadmap for the progressive deployment and parallel development of existing and increasingly efficient and reliable cryocoolers provides a clear path to realizing the performance benefits of SME in wireless communications, and serving the established need for universal and seamless communications.

7. ACKNOWLEDGEMENT

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8. REFERENCES

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