Superconductors and Cryogenics for Future Communication Systems

Matthias Klauda, Tobias Kässer, Bernd Mayer, Christian Neumann, Frank Schnell, Bachitor Aminov, Arno Baumfalk, Heinz Chaloupka, *Member, IEEE*, Serguei Kolesov, Helmut Piel, Norbert Klein, Stefan Schornstein, and Martin Bareiss

***Abstract*—In the framework of a German research program on "superconductors and ceramics for future communication technology," efforts are undertaken to demonstrate the feasibility of cryogenic and high-temperature superconductor technology for applications in communication satellites and base transceiver stations (BTS's) for terrestrial mobile communication. For the receiver front end of C-band satellites, noise reduction filters as well as input-multiplexer channel filters have been developed. A three-channel output multiplexer was composed of dielectric hemisphere filters with elliptic response. Associated encapsulation and cooling issues for spaceborn systems were investigated and an in-orbit demonstration of the complete setup will be performed on the International Space Station. Activities toward applications in terrestrial mobile communication are focused on BTS cryogenic front ends with single preselect filters of superior selectivity, and on reconfigurable front ends allowing some electronically controlled change in the preselection frequency response. A first version of a demonstrator for a cryogenic BTS front end was developed.**

***Index Terms*—Base-station technology, communication satellites, high-temperature superconductors, microwave filters.**

I. Introduction

MORE THAN ten years after the discovery of high-temperature superconductors (HTS's), passive microwave components for communication systems are considered to be one of the major application of this new material class. Therefore, strongly progressing international research and development (R&D) activities were started already shortly after the discovery [1]. From the beginning of these activities, the issues of miniaturization and performance improvement of communication systems with respect to selectivity, losses, and noise figure have been considered as the main benefits of HTS devices and subsystems. In the proceeding years of ongoing R&D activities, the complicated material issues [2] and the difficult preparation of HTS thin films with sufficient and reliable quality on the one hand, plus the issues of cryogenic cooling on the other hand, have turned out to be the major obstacles on the way to commercial applications of HTS's.

Within the last five years, significant progress has been achieved all over the world in manufacturing high-performance RF subsystems and systems with demonstrator capability. However, the commercial success thus far has not met the optimistic predictions claimed during the last decade, in particular, within the field of mobile communications. The main reason for this seems to be the precautions of the customers with respect to high costs and reliability of cryogenic cooling.

In the ongoing German program "Superconductors and Ceramics for Future Communication Technology," funded by the German Ministry of Education and Research, major efforts will be undertaken with respect to the following:

- demonstration of perspectives of cryogenic systems, including HTS devices, assembly technologies and cooling, evaluation of system benefits and comparison between superconducting and normal conducting cryogenic equipment will be one important issue;
- demonstration of the feasibility of cryogenic and HTS technology for commercial applications with emphasis on reliability, reproducibility, and cost effectiveness of the manufacturing processes;
- demonstration of a reliable, efficient, and cost-effective cooling technology.

The program is divided into five subprojects devoted to:

- superconductors, novel ceramics, and cryogenics for satellite communication;
- superconductors for mobile communications;
- superconductors and novel ceramics for directional broadcasting;
- cryocoolers and cryopackaging;
- superconducting materials: manufacturing, characterization, and qualification.

For the subprograms devoted to microwave subsystems, the first step will be the demonstration of the above-mentioned issues for systems with conventional architecture (e.g., transparent satellite payloads) and testing of these systems under realistic environmental conditions. An important part of this

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M. Klauda, T. Kässer, and B. Mayer are with Space Communication Systems, Bosch Telecom GmbH, D-71520 Backnang, Germany.

C. Neumann and F. Schnell are with Corporate Research and Development, Robert Bosch GmbH, D-70049 Stuttgart, Germany.

B. Aminov and H. Piel are with Cryoyelectra GmbH, D-42287 Wuppertal, Germany.

A. Baumfalk is with the Department of Electrical Engineering, University of Wuppertal, D-42119 Wuppertal, Germany.

H. Chaloupka and S. Kolesov are with Cryoyelectra GmbH, D-42287 Wuppertal, Germany, and are also with the Department of Electrical Engineering, University of Wuppertal, D-42119 Wuppertal, Germany.

N. Klein is with the Institut für Festkörperphysik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany.

S. Schornstein was with the Institut für Festkörperphysik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany. He is currently at Im Klapphof 33C, D-50670 Köln, Germany.

M. Bareiss is with the Department of Mechanical Engineering, University Paderborn, D-59494 Soest, Germany.

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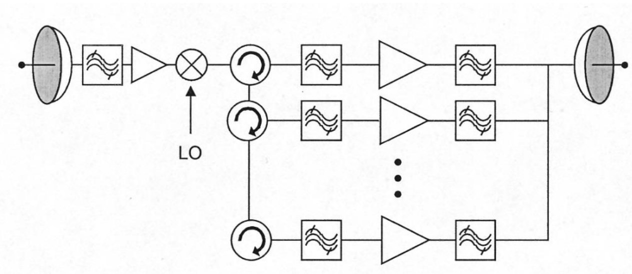

Fig. 1. Schematic block diagram of a conventional transparent satellite payload.

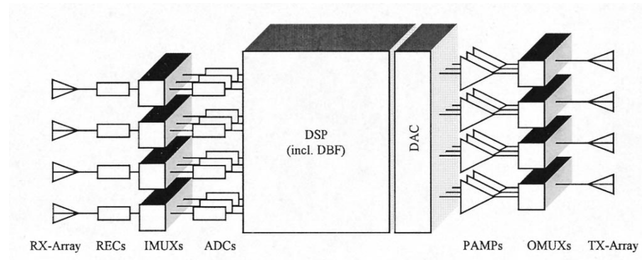

Fig. 2. Block diagram of a possible future regenerative satellite payload (RX: receive side, REC: receivers, IMUX: input multiplexer, ADC: analog–digital-converter, DSP: digital signal processing, DBF: digital beam forming, DAC: digital–analog-converter, PAMP: power amplifier, OMUX: output multiplexer, TX: transmit-side).

phase will be the development of an in-orbit demonstration experiment for satellite communication to be tested on the International Space Station at the European Technology Exposure Facility (EuTEF).

The subprograms dealing with cryogenics and HTS materials will define and specify the material basis for the envisaged commercial applications of HTS by:

- development of a reproducible HTS thin-film deposition technology with emphasis on qualification employing significant characterization methods;
- development of a Chrysler with emphasis on long lifetime and high power efficiency and compatibility for various applications in communication systems.

In the following, first results obtained within the programs:

- satellite communication;
- terrestrial mobile communication;
- cryogenics

will be presented and discussed.

II. Satellite Communication

Satellite payloads are essentially intelligent spaceborn mirrors, which receive an up-link signal with very low intensity and transmit the signal after some processing down to earth. "Transparent" transponders just transform the signal to a down-link frequency in order to avoid interferences between inbound and outbound beams and amplify it. "Regenerative" transponders also add "some" data processing on the signal.

A. Conventional Payload Architectures

Fig. 1 depicts a schematic and simplified block diagram of a conventional "transparent" communication payload with the functional units antenna, preselection filtering, low-noise amplification, down conversion, input multiplexer (IMUX), power amplifier, output multiplexer (OMUX), and transmit antenna. Further details like, e.g., switch matrices, isolators, or additional passive intermodulation product (PIMP) and low-pass filters, are omitted for simplicity. Since present high-power amplifiers (HPA's) show linear behavior only within quite narrow frequency ranges, multiplexing of the incoming broad-band signal (e.g., 500–700 MHz) into channels of bandwidths around 35–75 MHz is necessary.

For the IMUX behind the low-noise amplification, insertion losses of some few decibels are tolerable, but very stringent requirements on the frequency behavior of each channel—with respect to variation of group delay and variation of insertion loss or steepness of the filter skirts—apply. Filters used in the IMUX are typically high-order equalized versions, which require quality factors of the single resonators of at least 8000 in order to meet the in-band specifications. State-of-the-art filter technology for the IMUX are dielectric or waveguide filters with Q factors between 8000 and 12 000 and channel masses of about 250–650 g.

On the other hand, for the OMUX, the losses of filters and combiner network play an essential role. Since the efficiencies of the power amplifiers range between 20%–60% and dc power in a satellite can be converted into launch cost by a factor of about 5000–15 000 (US$) per watt, it is highly desirable not to loose the expensive amplifier power within the OMUX. Typical OMUX filters are four– to five-pole waveguide filters with losses of about 0.4 dB per channel (including losses of the complete infrastructure like tuning mechanisms and antennas) and masses of about 300–400 g.

B. Future Concepts

Fig. 2 depicts one possible setup of a future multiple beam regenerative transponder [3]. Without going into the details of this architecture, the essential benefit of this concept is the possibility to change the links between various receive and transmit beams almost arbitrarily. Of course, the degree of freedom for signal transmission and, thereby, transmission capacity, is considerably enhanced. The drawback of this concept is, of course, the high number of multiplexers, filters, and antenna elements, which demands for an extreme miniaturization of the single RF components at a constant or even enhanced level of RF performance with respect to losses, noise, and spectral efficiency.[1] Many other future system architectures discussed currently impose similar requirements on the analog components of the payload.

HTS's and cryogenic subsystems offer the perspectives of:

- minimization of mass and volume by substitution of bulky and heavy waveguide components by extremely compact planar devices, e.g., 1-kg payload mass causes launch costs for a geostationary orbit of about 50 000 (US$);
- minimization of losses and thereby a reduction of noise figures, which means reduced power consumption of the payload as well as improved transmission capacity (an

[1]The term "spectral efficiency" describes the ratio of useful bandwidth of a multiplexer (sum of the bandwidths of the individual RF channels) and the total bandwidth (sum of useful bandwidth and all guard bands between the channels).

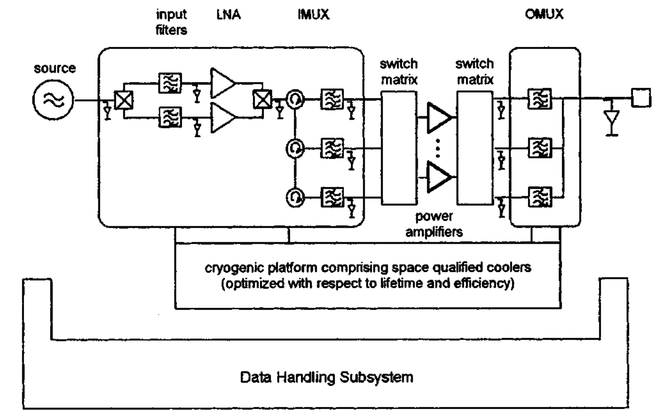

Fig. 3. Setup of the Bosch space experiment (NR: noise reduction, LNA: low-noise amplifier, IMUX: input multiplexer, OMUX: output multiplexer, PAMP: power amplifier).

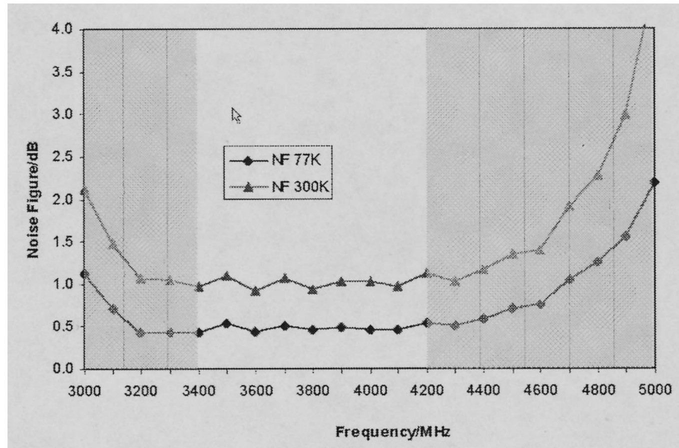

Fig. 4. Noise figures of the LNA at room temperature and 77 K.

improvement of 3 dB in system noise figures essentially means saving one complete transponder);

- optimization of spectral efficiency due to the possibility of much steeper filter skirts at a given loss or performance level.

Regardless of all advantages of HTS and cryogenic systems, satellite communication is a very conservative business with severe precautions and concerns against technologies that require, e.g., active cryocooling by a piston engine with moving parts in it—partially even at temperatures of -200 °C or less. The possibility of a failure in the cooling mechanism or in the assembly—which, as experience shows, indeed cannot be ruled out completely—or in the mounting and assembly technologies operating within an incredibly deep temperature range do not help this new technology to get a real chance to demonstrate its benefits in a real commercial program. Therefore, in the last few years, several programs have been set up, which demonstrate feasibility of cryocooling of superconducting RF components as well as the long-term stability of these new compounds and the technologies around them under space environment. The most prominent example is perhaps the recently launched HTSSE II experiment [4], which flies on the ARGOS satellite and comprises a colorful variety of HTS-based subsystems like receive side multiplexers, delay lines, etc.

Within the framework of the program "Superconductors and Novel Ceramics for Future Communication Technology," a space demonstration experiment will be developed and flown on the International Space Station.[2] In contrast to former space experiments, this experiment will simulate a commercial communication payload as far as possible under the given experimental boundary conditions. It consists of a receive section (front end and IMUX based on HTS technology) and a cryogenic transmit unit (OMUX), as shown in Fig. 3. Due to limited resources, there will be no RF link between earth and the experiment, but a self-analyzing setup, mainly based on a sophisticated data-handling system instead. Instead of typical numbers of channels of 30–60 in a commercial payload, the experiment presented here only will have three transmission channels within the satellite C-band between 3.7 and 4.2 GHz. While for the three-channel frequencies, a discrete RF signal will be applied by an RF source, all interesting points in the experiments will be monitored by RF power measurements. In the following, the actual state of breadboard activities on the HTS space experiment will be presented and discussed.

C. *HTS Applications for the Receive Unit*

As stated above, on the **receive side** of a satellite payload, noise reduction filters and channel filters of the IMUX have extremely high-performance requirements with respect to insertion loss (noise-reduction filter) or selectivity and in-band-behavior (IMUX channel filters). HTS materials now offer the possibility to replace the heavy and bulky conventional filters like waveguide or dielectric components by planar microstrip or coplanar components [5], [6], saving mass and volume to a considerable extent while offering an equivalent or even better performance.

In the ongoing programs, eight-pole noise reduction filters with bandwidths between 600 to 800 MHz for the satellite C-band have been developed [6]. Microstrip resonators with strong couplings were used to realize the large bandwidths of around 20%. We currently achieve insertion losses well below 0.1 dB. The filters have a total mass of about 40 g. A further mass reduction of 5–10 g can be expected by further optimization of the packaging.

The low-noise amplifier (LNA) for frequencies from 3.2 to 4.3 GHz is based on a commercial two-stage design, which shows noise figures of 0.5 dB at temperatures of 77K, compared to 1.1 dB at room temperature (Fig. 4).

As an example for a complete HTS unit, Fig. 5 shows the integrated receiver front end, consisting of two redundant branches of the noise reduction filter and LNA. Behind the input port (lower right-hand-side corner of Fig. 5) and the HTS filters, as well as in front of the output port (upper left-hand-side corner of Fig. 5), couplers and power measurement diodes are installed in order to check the functionality of the system.

IMUX channel filters according to specifications of a commercial program (eight-pole quasi-elliptic design) have been designed and produced based on HTS microstrip technology [6]. The weight of this filter is comparable to the preselect filter. To

[2]The experiment will be part of the European Space Agency (ESA) platform EuTEF in the "Early Utilization Phase" of this experimental platform.

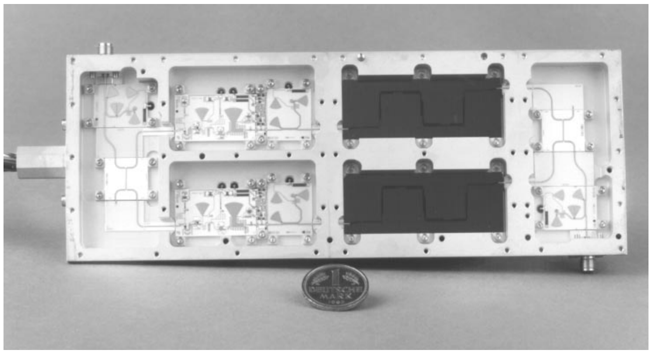

Fig. 5. Integrated receiver front-end unit with HTS noise-reduction filters and LNA's.

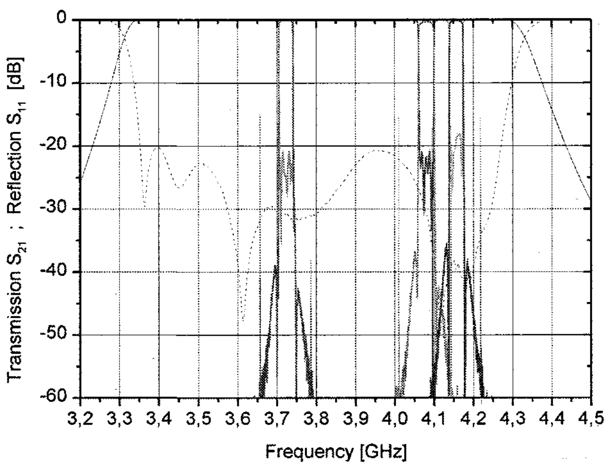

Fig. 6. Transmission and reflection characteristics of IMUX channel filters.

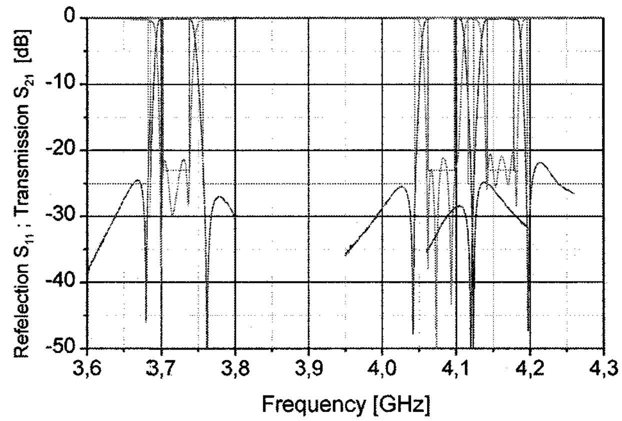

Fig. 7. Transmission and reflection characteristics of OMUX channel filters.

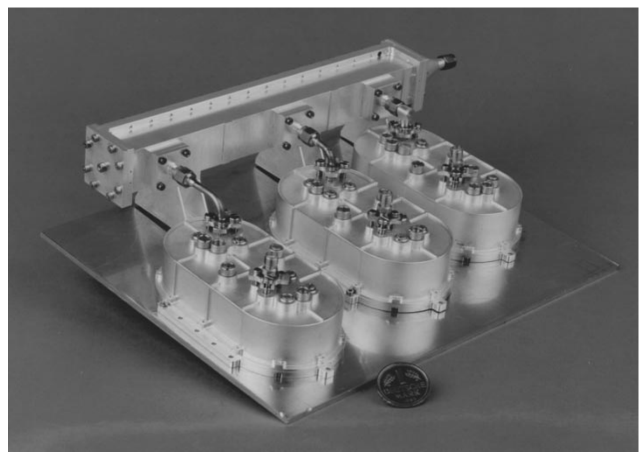

Fig. 8. Cryogenic three-channel OMUX (C-band) for the Bosch space experiment, based on dielectric hemisphere filters.

fulfill the specifications in group delay and flatness of the insertion loss in the transmitted band, an additional equalizer coupled to the filter by a circulator is employed. Fig. 6 shows the characteristics of the three IMUX channels. Integration of filter and equalizer will end up in a total mass of about 80 g per channel.

D. HTS and Cryotechnology for the Transmit Unit

For the **transmit side** of the payload, the OMUX has very high requirements with respect to power-handling capability and loss behavior of the filters. During the last two years, several HTS filters have been shown, which overcome the power-handling problem by employing resonator structures and modes with smooth and uniform current distribution within the superconductor materials [7]–[11]. On the other hand, a high power-handling capability alone is not sufficient for a beneficial use of superconducting or cryogenic filters. Due to the limited power of the cooling device, the heat load due to losses in the filters, combiner network, and connectors have to be minimized as far as possible. For the cryogenic or HTS filters, it can be demonstrated that quality factors of below about 100 000 (compared to about 10 000 for conventional OMUX filters) mean too high losses and, therefore, too high cooling powers to ensure a positive system balance. The resonator concepts given in [8]–[10] (HTS disc resonators) and [11] (hemisphere dielectric resonators) show power-handling capabilities for the superconducting resonators of several 10 kW of oscillating power and quality factors of about 100 000 at operating temperatures of 77K. By using cryogenic dielectric resonator filters without employing HTS materials [11], the operating temperatures can be enhanced toward about 120 K without significant degradation of the filter losses. Even at these temperatures, single resonator quality factors of 85 000 have been achieved. The higher operating power also improves the efficiency of the cryocooler and, therefore, releases the requirements on the transmit system losses considerably.

Fig. 7 shows the filter characteristics of a three-channel OMUX, based on four-pole dielectric hemisphere filters with elliptic filter response. The combiner network is a normal-conducting coaxial waveguide, which was optimized with respect to losses, weight, and volume. The OMUX is shown in Fig. 8.

Furthermore, for the transmit side, topics like cables and packaging have to be addressed very thoroughly. A specific example are the RF connectors from the cold HTS device to the warm surrounding. On one hand, for the reasons mentioned above, extremely low-loss connections have to be used; on the other hand, the heat load due to the thermal conductivity of the cables has to be minimized. Within the ongoing program at Bosch, special connectors with low electric losses (less than 0.03 dB at room temperature) and high thermal resistivity (more than 1000 K/W) in the breadboard design have been

Fig. 9. Cryocoupler for a cryogenic OMUX. The device has an insertion loss of less than 0.03 dB, a thermal resistivity of more than 1000 K/W, and has been tested for power levels up to 200 W.

developed to overcome this problem. Fig. 9 shows an example of these "cryocouplers" for OMUX applications.

E. System Description

The key issue of application of HTS and cryotechnology for commercial satellite communication will be the availability of a reliable, efficient, and reasonably priced cooling technology. This not only—but in the main instance—affects the cryocooler itself. The state-of-the-art technology in many aspects does not fit very well the need of broader commercial application since, in most cases, it is far too expensive, far too inefficient, and far too bulky. As will be described in detail in Section IV, the intent of this program is to adapt tactical cryocoolers with reasonably good efficiency, small weight and volume, and medium range prices in a cost-efficient way toward commercial (space) applications. Main improvements indeed have to be done with respect to lifetime of the coolers, which currently range somewhere between 10 000–20 000 h mean time to failure (MTTF).

Nevertheless, for a cryogenic spaceborn system, some redundancy for the single-point failure of a cryocooler drop out essentially has to be provided. In contrast to other concepts with redundant electronic units or redundant compressors [12], in this program, a redundancy of the complete cooler unit including an electronic unit, compressor, and cold head is foreseen in order to provide maximum reliability. Since, in this case, a switched off or defect cooler connected to the cryogenic part of the payload will introduce a parasitic heat load in the range of about 800 mW, some mechanism for separating the nonoperating cooler from the cryo-unit has to be implemented. In the case of our experiment, this is done by a thermal switch, based on principles of thermal expansion and developed in cooperation with the Institut für Luft und Kältetechnik, Dresden, Germany. The mechanical setup of the breadboard version is shown in Fig. 10. The thermal resistivity in the "on" state is about 1 K/W, and in the "off" state is about 1500 K/W.

Fig. 11 shows a first setup of the experiment [13]. The system essentially consists of two platforms. The warm platform contains the conventional components like switch matrix, power amplifiers, measurement and telemetry equipment, the compressor, and the heat reject part of the cryocooler. The cryogenic platform is mounted with minimized thermal contact to the environment (by specially designed suspensions and radiation shields). It contains a receive unit (front end and IMUX) and transmit unit and is connected to the environment by electrically and thermally optimized feedthroughs for RF and dc signals.

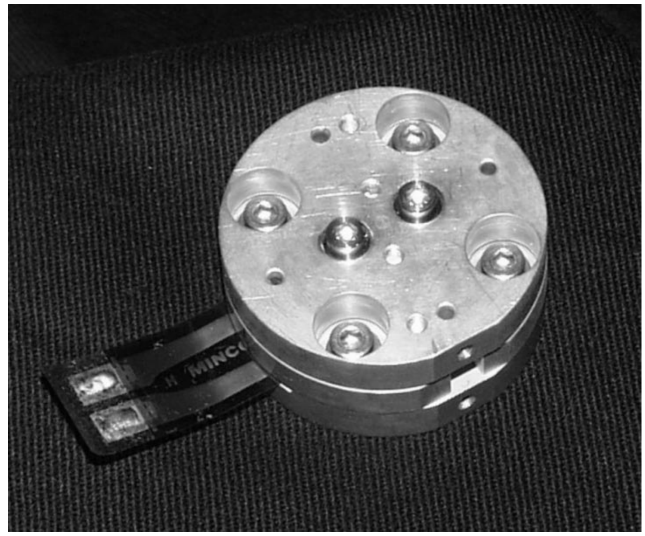

Fig. 10. Mechanical setup of the first version of the thermal switch of the Bosch space experiment.

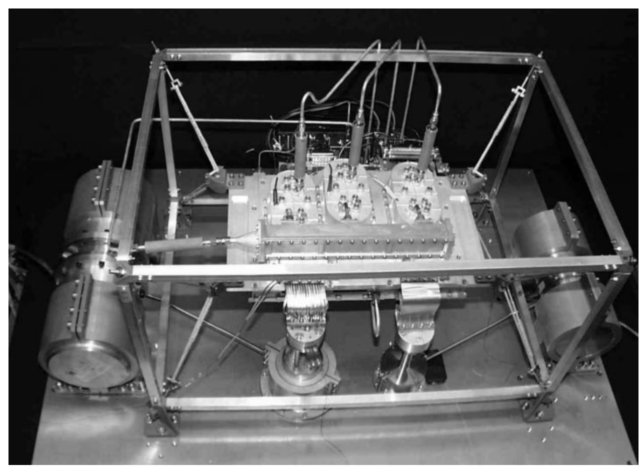

Fig. 11. First experimental setup ("breadboard") of the demonstrator experiment. The cryogenic platform is suspended within a metal frame. On top of the cryogenic platform, the OMUX is located, the IMUX and front end are positioned on the down side.

F. Further Activities

The experiment presented above will mainly demonstrate the following two issues.

- HTS and cryotechnology is able to take over its part in a commercial satellite payload.
- HTS and cryotechnology do have the ability to pay off in a conventional payload architecture—provided that some boundary conditions like number of channels, efficiency of the cooling system, etc., fit well.

As stated above for future satellite architectures, HTS's can also give significant beneficial contributions to the system. In many cases, the ideas behind these system concepts are quite analog to concepts followed up in terrestrial communication technology. One of the main advantages of the ongoing program, therefore, is to connect the various fields of application like satellite communication, wireless terrestrial communication, and directional broadcasting, and to extract as many synergies as possible from the parallel work on these fields.

III. Terrestrial Mobile Communication

This sub-project deals with the development of HTS components and subsystems for use in base transceiver stations (BTS's) of digital mobile communication systems of the second (e.g., GSM, DAMPS/IS-136, PDC, etc.) and forthcoming third generation (e.g., W-CDMA, cdma2000). The activities are based on the presumption that, due to the cooling burden, an implementation of HTS technology (e.g., [2], [14]–[18]) will only occur if:

- with the employed HTS components, a performance is achieved, which is not accessible in conventional technology;
- if the superior component performance can be transformed into a significant system benefit;
- if many different components benefit from cryogenic temperatures and share a common cooler system.

A. HTS Preselect Filter in BTS Receiver Front End

Fig. 12 depicts schematically a BTS multicarrier receiver front end. It comprises the functions preselection (RF bandpass), preamplification (LNA), downconversion (mixer), and analog-to-digital conversion (ADC). Two alternative approaches for the realization of (frequency) channel selectivity are shown. In the traditional architecture (upper right-hand side), a bank of narrow-band parallel receiver chains composed of mixer, IF bandpass, IF amplifier, and ADC (with bandpass sampling) are employed. Here, channel selection is performed by means of the narrow-band IF filters. Future "software radio architectures" (lower right-hand side) will employ a wide-band mixer, followed by a wide-band IF bandpass and ADC, and the channel separation is realized in digital signal processing (DSP) [19].

The function of the preselect bandpass filter is to sufficiently reject spectral components outside of the access band (bandwidth ΔF) in order to avoid [3]:

1) undesired image receipt;
2) conversion into in-band frequency components via intermodulation due to nonlinearities in the LNA and mixer(s);
3) desensitization and saturation of the LNA and mixer(s).

With the application of novel HTS bandpass filters as preselect filters, a conventionally unachievable steepness $S_F = L_{s,\min}/\delta f$ of the filter skirts (see Fig. 12), combined with low values of the (dissipative) passband insertion loss L_0, becomes available. Consequently, a working package is focused on the development of bandpass filters with ultimate steepness of the filter skirts. This includes identification of physical and technological limits for the achievable steepness, as well as the realization of prototype BTS receiver front ends (see Section III-B).

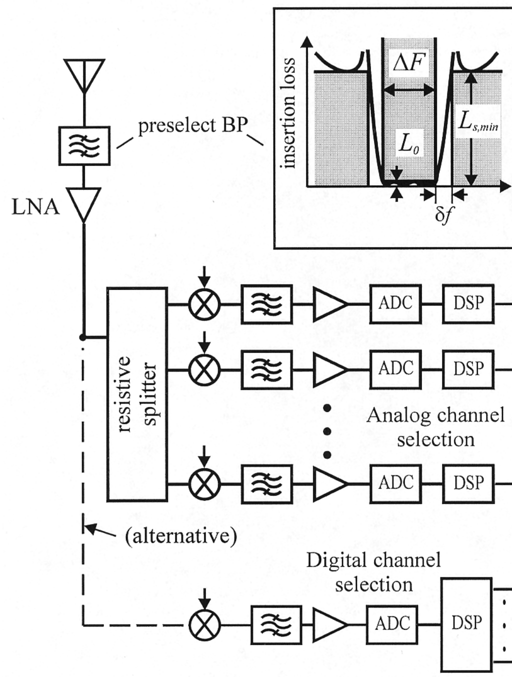

Fig. 12. Front end of multicarrier BTS receiver with analog (center part) and digital (lower) channel selection. Notations used for the specifications of a preselect bandpass filter (upper part).

Due to the general relationship between frequency resolution and integration time, a small transition width δf is always accompanied by a large group delay, with the maximum group delay value τ_T occurring in the transition region of the filter. For a required skirt steepness S_F, a lower limit with $\tau_T \geq \beta_0 \cdot S_F$ holds. The value of β_0 depends on the minimum passband return loss, but for a crude estimation, $\beta_0 \approx 0.01$/dB can be used for typical values of the passband return loss. It is important to note that only filters with real elliptic response are approaching this lower limit. These filters possess $M = N - 1$ transmission zeros at finite frequencies if N denotes the number of poles. In case of quasi-elliptic filters with $0 < M < N - 1$ and Chebyshev filters with $M = 0$, a larger group delay $\tau_T = \beta \cdot S_F$ is required for a given steepness S_F. The "group delay efficiency" $\eta_G = \beta_0/\beta$ turns out to be for a given order N a monotonically increasing function of M, with $\eta_G \approx 1/3$ for Chebyshev and $\eta_G \approx 1$ for (real) elliptic filters.

It is important to keep τ_T for a given value of S_F as low as possible since the degradation of the filter response by dissipative losses is proportional to τ_T. The product of group delay τ_T and frequency f together with the unloaded quality factor Q_0 of the resonators determines via

$$\frac{P_{\text{diss}}}{P_{\text{inc}}} = \frac{2\pi f \tau_T}{1 + 2\pi f \tau_T} \tag{1}$$

the portion P_{diss} of the incident power P_{inc}, which is dissipated. If 20% power loss is taken as limit for the acceptable degradation, the required unloaded quality factor of the resonators is from (1) derived as

$$Q_0 > 250 \cdot \frac{1}{\eta_G} \cdot \frac{f}{\text{GHz}} \cdot \frac{S_F}{\text{dB/MHz}}. \tag{2}$$

The important conclusion from (2) is that, for a maximum steepness, both the unloaded quality factor Q_0 as well as η_G have to be maximized. With this goal in mind, a novel filter structure with $M = N - 1$ was developed. The following issues turned out to be most important for a successful realization of a filter prototype.

1) Typically, a minimum stopband attenuation $L_{s,\min} > 80$ dB is required. Therefore, cross coupling between "output-near" and "input-near" resonators in order to produce $N - 1$ transmission zeros (for $\eta_G \rightarrow 1$) is prohibited. Furthermore, coupling between the ports via surface-wave excitation has to be considerably suppressed by a minimization of surface-wave excitation.
2) Undesired parasitic coupling between resonators causes a degradation of the transmission zeros and has, therefore, to be suppressed, e.g., by means of suitable "shields."
3) In order to achieve at around 2-GHz unloaded Q values $>$50 000, the loss contributions from the surrounding housing as well as from imperfect contact between wafer ground plane and housing become important and require special technological means.
4) Extremely steep skirts also require special care with respect to a fixation of the tuning screws and temperature stability with respect to mechanical expansion.

The desired steep skirts are associated with a large group delay of around 1 μs for frequencies in and close to the transition region. The strong frequency dependence of the group delay at the passband edges causes intersymbol interference and, therefore, must be compensated by an additional analog allpass (equalizer) in the RF or IF part, or by equalization in DSP.

From a system point-of-view, steeper filter skirts provide the network designer with the freedom to use significantly narrower spacing between frequency bands with largely different peak and/or mean power level. Due to the rapidly increasing number of subscribers and the necessity to include multimedia capability, the demands for reduced guard bands become increasingly important. Some examples for systems where a large payoff of highly selective HTS filters are expected are as follows (see also [3]).

1) Within the European Universal Mobile Telecommunications System (UMTS) standard some radio base-stations will have to accommodate the coexistence of wide-band (W) CDMA in paired frequency bands in the frequency-duplex mode (FDD), and time-division multiple access (TDMA)/CDMA in unpaired bands in the TDD mode. Due to the fact that the TDD band with high-power-level transmits signals in bands allocated adjacent to receive-only FDD bands, extremely high selectivity requirements are posed on the filter if a wide guard band (and, therefore, a relatively low-frequency efficiency) must be avoided.
2) In some regions, new W-CDMA bands will be located as close as 2 MHz to the band edge of existing personal communication systems (PCS's).
3) In hierarchical cell structures, the uplink signals of nearby microcells arrive at the macrocell BTS (umbrella cell) at a much higher power level as the uplink signals of remote users of the macrocell. This again requires sharp filter skirts for suppression of strong interfering signals.

Besides superior selectivity, a tower-mounted cryogenic front end also represents a mean to increase receiver sensitivity, alternatively or additionally to other means as an increased tower height and directive and adaptive antennas. If, for mobile communication frequencies (0.9–2 GHz), a conventional bandpass–LNA subsystem at room temperature is replaced with a cryogenic HTS–bandpass–LNA subsystem, typically up to 2-dB improvement in receiver noise figure is obtained. This reduction is based on: 1) the reduced LNA noise due to cooling (typically 0.8–1 dB at 300 K and 0.4 dB at 60 K); 2) the reduced physical temperature of the cooled preselection filter (reduction by 0.2 dB for 1-dB insertion loss of filter); and 3) the reduced insertion loss of HTS filters in comparison to conventional filters. For standard filter specifications, contributions 1) and 2) usually dominate contribution 3). Hence, the noise-figure reduction is mainly due to the lower temperature and not so much due to the low HTS losses. This situation changes for filters with unconventionally steep skirts, where the low losses in HTS are also essential for achieving a low receiver noise figure.

A necessary condition for transforming a reduced receiver noise figure into a system benefit is a low antenna noise temperature $150 < T_A < 300$ K and, therefore, the absence of strong man-made noise coming from auto vehicles (ignition, etc.) and industrial plants. With this man-made noise, the antenna noise temperature can, in urban areas, increase up to 2000 K.

In noise-limited scenarios, higher sensitivity transforms into an increased coverage, allowing, e.g., less base-stations for a given area and/or higher quality of service in strongly shadowed subareas. For areas with higher traffic, the maximum cell radius is not limited by link budget considerations, but rather by capacity considerations (interference-limited system). Here, the reduction of receiver noise under certain circumstances can be transformed into increased capacity. This is especially true for CDMA systems, where for a given signal-to-interference-and-noise ratio (SINR) [3] reduced (thermal) noise allows a higher multiple-access-noise level and, therefore, more simultaneous users per area.

B. Demonstrator for an HTS Preselection Filter with Cryogenic LNA

In order to demonstrate the feasibility of a cryogenic BTS receiver front end composed of an HTS preselection filter followed by a cryogenic LNA, the demonstrator shown in Fig. 13 has been designed, manufactured, and tested. The demonstrator consists of the recipient, which forms the vacuum enclosure incorporating the filter–LNA ring, the cryocooler supplying the necessary cooling power, and the control electronics with all necessary cabling.

Fig. 13. Demonstrator for a cryogenic BTS receiver front end.

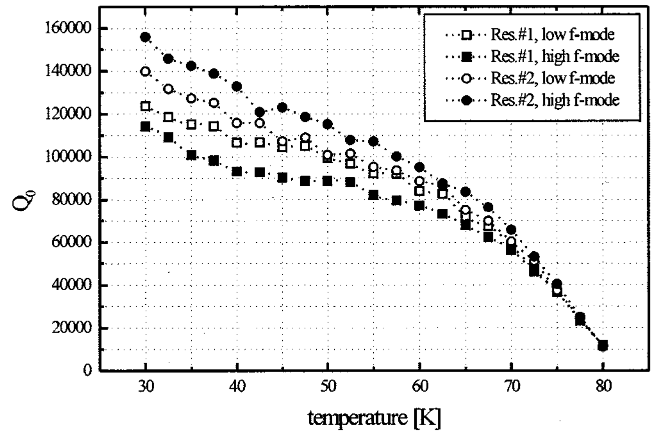

Fig. 15. Temperature dependence of the unloaded Q factor of the modes of two different dual-mode resonators.

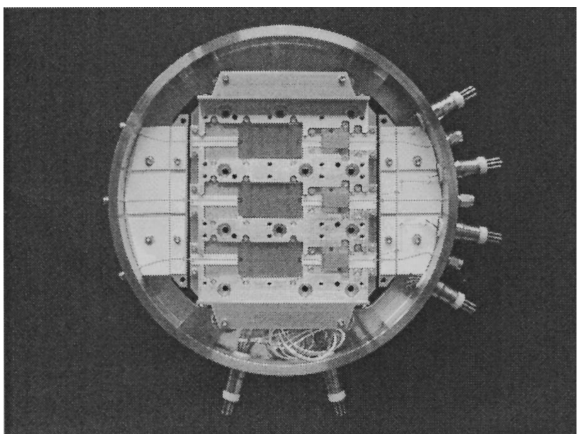

Fig. 14. Three-channel filter–LNA assembly.

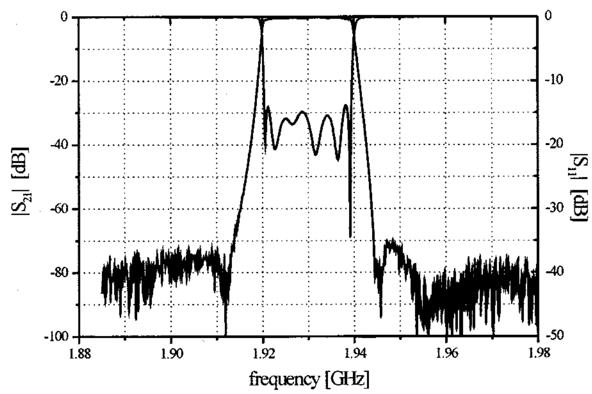

Fig. 16. Frequency characteristics of a nine-pole planar elliptic filter at 60 K.

Cooling of the cryogenic part of the filter–LNA ring is provided by a Stirling cooler developed and marketed by Leybold, Cologne, Germany. It supplies 6 W at a temperature of 77 K and this power falls off almost linearly to zero at about 38 K. The cryogenic part of the filter–LNA assembly is operated in the temperature range from 60–75 K. Therefore, a permanent vacuum below 10^{-5} mbar is maintained in the enclosure to provide effective and reliable vacuum insulation during the operation.

A view into the open filter–LNA ring is depicted in Fig. 14. The ring contains the thermally isolated cryogenic part with three channels composed by an HTS filter followed by an LNA. The LNA's were purchased from MITEQ Inc., Hauppauge, NY, and possess a gain of about 17 dB and a noise figure of about 0.2 dB at 77 K in contrast to 0.8 dB at room temperature. Room-temperature input and output microwave lines, as well as the dc feed lines for the LNA's, are patterned on alumina gold-plated substrates. The interconnects between the parts of the channels were performed by 25-μm aluminum wire bonding. The cryogenic part is thermally isolated from the room temperature parts by a 2-mm wide gap and the microstrip lines are bridged by two level wire bonding.

The filters implemented into the ring are nine-pole elliptic HTS filters on sapphire substrates [20]. The building block of the filter is a dual-mode resonator exhibiting two controllable transmission zeros in addition to two poles. Temperature dependence of the unloaded Q factor of the modes of two different dual-mode resonators is shown in Fig. 15. According to (2), filters with steepness from 100 to 240 dB/MHz can be realized using this concept for operating temperatures lower than 70 K. The frequency characteristic of one of the filters at 60 K is depicted in Fig. 16. The filter is centered at 1.93 GHz and has the fractional bandwidth of about 1% with minimum reflection loss of 15 dB, midband insertion loss of about 0.1 dB, and minimum stopband attenuation of about 70 dB. The asymmetry of the filter characteristics is due to some couplings, which were not taken into account during the simulations. The steepness of the skirts is 15 and 20 dB/MHz at the lower and upper band edges, respectively. This compares to a theoretical values of 7.5 dB/MHz for the same-order Chebyshev and 25 dB/MHz for the same-order real elliptic filters. Filters of higher order up to $N = 17$ are now at the design stage.

C. HTS in BTS Transmitter Units

The transmitter units of conventional base-stations include two different types of filters, namely transmitter combiners for combining separately power-amplified carriers into a common antenna and transmitter filters for the rejecting out-of-band components in the output spectrum of the HPA's. At present, strong efforts are made in order to replace the transmitter combiner architecture with separate HPA's for each carrier by a highly linear multicarrier power amplifier.

Application of HTS technology to filter in transmitter units can be motivated by the goal to reduce the required output power of the HPA's for a given power at the antenna port due to a significantly reduced filter insertion loss. However, the realization of planar HTS filters with high power-handling capability is rendered difficult by the fact that a significant nonlinear response of the conductivity occurs if the RF surface magnetic field strength exceeds a value on the order of 10 A/cm [3], [7]. Due to the current peaking at the edge of most planar resonators with edge-parallel currents, this value is already reached for an oscillating power (product of stored field energy and frequency, see e.g., [3]) on the order of 50 W. The oscillating power in a resonator of a bandpass filter depends via

$$\omega W = \zeta \cdot \frac{f_0}{\Delta f} \cdot P_{\text{inc}} \tag{3}$$

on the fractional bandwidth $\Delta f / f_0$ and the incident power P_{inc}. The factor ζ depends on the frequency (within the passband), on the filter type (Chebyshev, quasi-elliptic, etc.) and on the position of the resonator in the filter structure. For frequencies close to the band edge, ζ reaches values on the order of 2–4, so that, e.g., the second resonator of a filter with 1% fractional bandwidth must handle an oscillating power of 10–20 kW if a power of 50 W is incident. At present, only two approaches are suited to meet this requirement for power handling in HTS technology, namely, the concept of edge-current-free disk resonators [10] and the concept of dielectric resonators with HTS endplates [11].

With YBCO disk resonators for the C-band (4 GHz) fabricated on sapphire substrate, an unloaded quality of 360 000 has been achieved at a temperature of 60 K. Further miniaturization could be realized using high-permittivity lanthalum aluminate ($LaAlO_3$) substrates. Utilizing an improved substrate material with reduced dielectric losses, an unloaded Q of 300 000 was measured at the same temperature [21]. A first approach for building a transmitter combiner comprising disk resonators, which are tuned via piezo actuators, has been reported in [22]. Additionally, elliptical four-pole filters composed of cross-coupled disk resonator structures have been developed as presented in [23].

D. HTS in a Reconfigurable Receiver Front End

The degrees of freedom (e.g., choice of bandwidth, modulation scheme, etc.) for the implementation of new services are restricted by the hardware of existing BTS's. In order to overcome these restrictions, reconfigurable BTS's (together with reconfigurable mobile stations) are envisaged. In principle, the software radio concept, where the ADC is shifted as close as possible toward the antenna and as many functions as possible are performed in a software-controlled manner in DSP, is a suitable mean for the realization of reconfigurable transceivers. However, the most severe hurdle in the realization of software radio architectures are dynamic range problems in the analog RF part (nonlinearities of the LNA and mixer) and the ADC (additionally to high sampling rate, high resolution required [19], [24]). By these reasons, adaptive RF prefiltering, which allows some electronically controlled change in the frequency response, is highly demanded [25], [26].

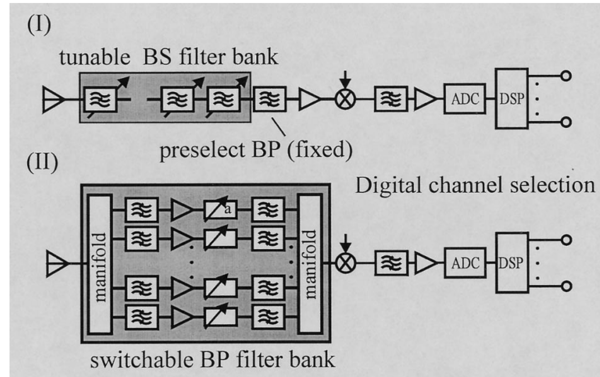

Fig. 17. Adaptive analog RF prefiltering. (I) Tunable BS filters in front of a fixed wide-band bandpass. (II) Switchable filter bank comprising of two contiguous multiplexers, LNA's, and cooled adjustable attenuators.

Fig. 17 illustrates two different architectures for adaptive analog prefiltering, which are both considered within the ongoing research project. In both cases, the starting point is a software radio front end according to the architecture shown in the lower part of Fig. 12. In the first concept (part (I) in Fig. 17), the fixed preselect bandpass covering the entire access bandwidth is retained, but a bank of tunable bandstop (BS) filters (e.g., notch filters) is placed in front of this fixed bandpass. A completely different approach with a switchable filterbank is shown in part (II) of Fig. 17. Here, narrow-band bandpass filters (5-MHz bandwidth) form a contiguous multiplexer, which is followed by LNA's and cooled attenuators. For signal recombination, another multiplexer is employed.

In the following, more details on the realization of subsystem (I) from Fig. 17 are given.

Notch filters are realized by means of cooled semiconductor GaAs varactors, as well as by cooled ferroelectric varactors. Comparison of achievable performance represents one goal of the project.

If a voltage-controlled varactor is inserted into a high-Q planar HTS resonator in order to allow for some electronic tuning of the resonant frequency, it causes the following severe problems.

1) Due to the fact that the quality factor Q_{var} of the currently available varactors is much lower than the quality factor $Q_{0,c}$ of the HTS resonator (without varactor), a Q-degradation occurs.
2) As a consequence of the short time constant associated with the physical effects employed, in addition to the desired capacitance variations with the applied bias voltage, an undesired nonlinear response to the RF field occurs. The latter effect leads to the generation of intermodulation and harmonic products.

For varactors, both the differential capacitance $C(v_0)$ and quality factor $Q_{\rm var}(v_0)$ are functions of bias voltage v_0. With $v_1 < v_0 < v_2$, the varactor tuning ratio $r_{\rm var}$ can be defined as

$$r_{\rm var} = 2\big|C(v_1) - C(v_2)\big| / \big(C(v_1) + C(v_2)\big). \qquad (4)$$

The product $r_{\rm var} \cdot Q_{\rm var,\, min}$ (with $Q_{\rm var}(v_0) \geq Q_{\rm var,\, min}$ in the tuning range) represents an important figure-of-merit for the varactor performance. The coupling strength between varactor and resonant circuit is described via the coupling coefficient $\Lambda = W_{\rm var}/W_{e,\, tot}$, which relates the stored energy in the varactor $W_{\rm var}$ to the totally stored electric field energy $W_{e,\, tot}$.

The fractional tuning range of the resonator $\delta f_0/f_0$ and the unloaded quality factor of the resonator Q_0 are via Λ related to the varactor parameter $r_{\rm var}$ and $Q_{\rm var,\, min}$ as follows:

$$\frac{\delta f_0}{f_0} = 0.5 \Lambda r_{\rm var} \qquad (5)$$

$$Q_0 = \frac{Q_{\rm var}}{\Lambda} \cdot \frac{1}{1 + (Q_{\rm var}/\Lambda Q_{0,\, c})} \qquad (6)$$

with $Q_{0,\, c}$ as the quality factor of the resonant circuit without a varactor. With tight coupling ($\Lambda \rightarrow 1$), a considerable large fractional tuning range for the resonator frequency is obtained at the cost of a low resonator quality factor. On the contrary, with weak coupling, Q_0 can approach values nearly as high as $Q_{0,\, c}$, but at the cost of a very small resonator frequency tuning range.

Several experiments with semiconductor varactors were performed at 2 GHz in the temperature range between 30–70 K. A typical result for an GaAs varactor shows for reverse bias between 3–12 V a variation of the differential capacitance between 0.6–0.34 pF, leading to a varactor tuning ratio $r_{\rm var} = 0.55$. In this bias range, the varactor quality factor $Q_{\rm var}$ varies between about 125–250. These varactors were implemented into planar HTS resonators with unloaded Q (without varactor) of about 50 000 at 60 K. With rather weak coupling ($\Lambda = 0.0037$), the resonant frequency can only be tuned by 2 MHz (0.1%), but the Q factor is kept as high as 20 000 ($v_0 = 3$ V) to 28 700 ($v_0 = 12$ V). In contrast, for tighter coupling with $\Lambda = 0.0225$, the resonant frequency can be tuned by 12 MHz at the cost of a reduced resonator quality factor in the order of 5000–9000.

IV. Cooling Technology

A. Overview

As mentioned in previous sections, the key issue for application of HTS for commercial satellite and terrestric communication will be the availability of suitable cooling technology, which has to meet the following requirements:

- high coefficient of performance (COP) of more than 5%@77 K, with the COP being understood as net cooling power/input power ratio;
- long maintenance-free lifetime of at least five years;
- operability under a wide range of thermal environmental conditions, depending on where and how the system will be installed actually;
- low cost and modest with respect to supply and logistic needs.

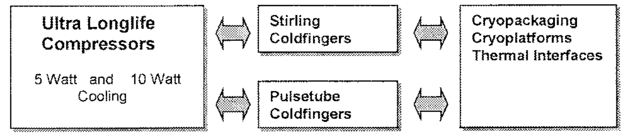

Fig. 18. Structure and objectives of cryocooler program.

None of the currently available cooling systems can meet all of these requirements. **Gifford–McMahon (GM)** coolers, for instance, though very well approved for laboratory, ultrahigh vacuum, and NMR applications, will hardly have the potential of a COP that high and a maintenance-free lifetime that long.

Tactical coolers, on the other hand, produced in fairly high volumes for mainly military infrared systems, are quite close to the mentioned COP requirement and can be operated under harsh conditions. Although lifetime of these coolers could be increased significantly in the last decade, it is still far below the required figure of at least five years and their costs are not in the range, which is acceptable for the commercial telecommunication market.

Coolers with demonstrated lifetimes of more than three years only exist for space applications.

Within this category, a "Stirling-type" **space cooler** was developed and qualified by Matra Marconi Space, Stevenage, U.K. [27] with a lifetime of five years. A "pulse-tube-type" spacecooler was developed and qualified by TRW, Redondo Beach, CA [28]. As designed for space applications, these coolers are built in very small volumes specific to their application in single space missions. Hence, they will hardly be able to meet cost targets for commercial telecommunication programs.

To close the gap between need and availability, it is one of the essentials of the subject program to develop coolers in accordance to the above listed requirements. The structure of this cryocooler program is outlined in Fig. 18.

Accordingly, two long-life compressors are under development, to cover applications within the two cooling power ranges of 5 and 10 W, respectively. Both compressors shall be operable with a Stirling or pulse-tube cold finger optionally. Development of components for thermal and mechanical adaption between cooler and HTS electronics will be addressed as well.

The team of companies and institutions working on this program consists of:

- AEG Infrarot Module (AIM) GmbH, Heilbronn, Germany, a leading company in infrared detector and cooler technology;
- Leybold Vakuum GmbH, Cologne, Germany, a leading company in vacuum technology ;
- Department of Applied Physics, University Giessen, Giessen, Germany, successful in pulse-tube research and development;
- Institut für Luft und Kältetechnik, Dresden, Germany a private laboratory, specializing in cryogenics.

B. R&D Approach

It was understood that the goal can be best achieved via linear-type Stirling compressors with flexural spring design. As already mentioned, both compressors (for 5 W, respectively,

Fig. 19. AIM SL200 cooler, a split Stirling cooler with linear drive compressor. Cooling power 3.5 W@77 K.

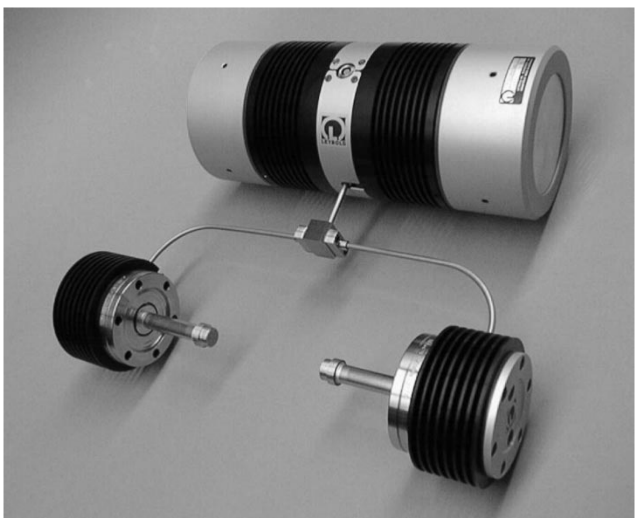

Fig. 20. Leybold cooler, a split Stirling cooler with linear drive compressor. Cooling power 6 W@77 K.

10-W cooling power) may optionally be operated with a Stirling or pulse-tube cold finger, both being designed to maximum cooling power and lifetime.

The program is based on the cooler technology of both industrial partners AIM GmbH and Leybold Vakuum GmbH. Development of the 5-W cooler originated from the AIM SL200 cooler, which is shown in Fig. 19.

The subject cooler is a linear-type Stirling cooler with a nominal cooling power of 3.5 W at 77 K, developed under sponsorship of the German Ministry for Research and Education (BMBF) as a first-generation cooler for HTS applications [29]. The similarity to tactical coolers shows that this cooler was developed on the basis of the subject technology.

Development of the 10-W cooler originated from the Leybold 6 W@77 K cooler, which is shown in Fig. 20. This cooler is a linear-type Stirling cooler as well, with nominal cooling power of 6 W at 77 K. This first-generation development was motivated by the U.S. Defense Advanced Research Projects Agency (DARPA) and the European Superconducting Systems for Communications (SUCOMS) programs [30]. The operation with two cold fingers, as shown in Fig. 20, is an optional way of arrangement in sensitive applications, where cold-finger vibration has to be canceled out. In usual applications, where cold-finger vibrations are tolerable to some extend, the subject cooler is operated with a single cold finger, resulting in a less expensive and more efficient configuration.

The maintenance-free lifetime of both basis coolers is calculated to be in the 1–3-year range, depending on the conditions under which the coolers are operated.

R&D of the pulse-tube cold fingers for both compressors, respectively, cooling power categories is underway in the Department of Applied Physics, University of Giessen, Giessen, Germany, where intensive pulse-tube cooler know-how has been established by various projects done on this subject [31], [32].

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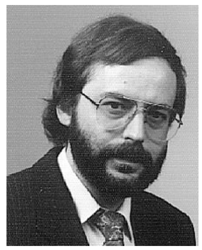
Matthias Klauda was born in Erlangen, Germany, in 1965. He received the diploma degree in physics from the University of Erlangen, Erlangen, Germany, in 1990. During his Ph.D. studies, he investigated electronic and magnetic properties of cuprate compounds.

Since 1994, he has been with Bosch Telecom GmbH, Backnang, Germany, where he is responsible for the development of superconducting and cryogenic components in the Space Communications Department.

Tobias Kässer received the diploma degree in physics from the University of Konstanz, Konstanz, Germany, in 1995, and the Ph.D. in electrical engineering from the University of Wuppertal, Wuppertal, Germany, in 1999.

He is currently with the Bosch Telecom GmbH, Backnang, Germany, where he is involved in the fields of passive microwave devices based on superconducting materials, as well as cryogenic front ends and IMUX's.



Bernd Mayer was born in Metzingen (near Stuttgart), Germany. He received the Dipl.-Ing. degree in electrical engineering from the University of Bochum, Bochum, Germany, in 1987, and the Dr.-Ing. degree from the Technical University Hamburg-Harburg, Hamburg, Germany, in 1992.

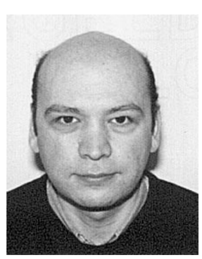
From 1992 to 1993, he was involved with millimeter-wave IMPATT oscillators at the Technical University of Munich. From 1993 to 1997, he was a Member of Staff at the German Aerospace Research Establishment, Oberpfaffenhofen, Germany, where he was involved with high-precision surface loss measurements of HTS's and HTS planar microwave circuits for satellite applications. Since 1997, he has been a Microwave Design Engineer at Bosch Telecom GmbH, Backnang, Germany, where he developed several waveguide switches and filters for satellite applications. He is currently a member of the HTS Group, in which he is responsible for a cryogenic OMUX.

Christian Neumann received the Dipl.-Phys. and the Ph.D. degrees from the University of Konstanz, Konstanz, Germany, in 1988 and 1991, respectively.

From 1992 to 1995, he was a Post-Doctoral Researcher at the Research Center, Institute of Technical Physics, Karlsruhe, Germany, with a one-year stay at the Superconductivity Research Laboratory, Tokyo, Japan, as an International Superconductivity Technology Center (ISTEC) Fellow. In 1995, he joined the Corporate Research and Development Center, Robert Bosch GmbH, Stuttgart, Germany, where he is currently involved with superconductivity for RF applications and new technologies.

Frank Schnell received the diploma degree from the University of Hamburg, Hamburg, Germany, where he was involved in the preparation and characterization of Josephson junctions, especially RF characterization.

Since 1998, he has been with Robert Bosch GmbH, Stuttgart, Germany. His field of work is the development and the qualification of HTS technology.

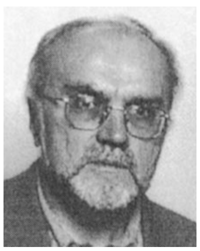


Bachtior Aminov was born in Dushanbe, Tadjikistan, Russia, in 1961. He received the diploma degree in physics and the candidate of Sc. degree (Ph.D.) in physics and mathematics from the Moscow State University, Moscow, Russia, in 1984 and 1990, respectively.

In 1992, he joined the Physics Department, University of Wuppertal, Wuppertal, Germany, where he has been involved in the First Applications of High-Temperature Superconductors in the High-Frequency Technique Project. Since 1995, he has been with Cryoelectra GmbH, Wuppertal, Germany. He is currently involved in the development of microwave superconductive components for mobile communication systems.

Arno Baumfalk was born in Solingen, Germany, on April 2, 1970. He received the Dipl.-Ing. degree in electrical engineering from University of Wuppertal, Wuppertal, Germany, in 1996, and is currently working toward the Ph.D. degree in electrical engineering at the University of Wuppertal.

He is currently with the University of Wuppertal as a Research Assistant, where he is involved in the field of high-power microwave devices based on HTS materials.



Heinz Chaloupka (S'68–M'69–SM'00) received the Dipl.-Ing. (M. Sc.) degree from the Technical University of Darmstadt, Darmstadt, Germany, in 1969, and the Dr.-Ing. (Ph.D.) degree in electrical engineering from the University of Bochum, Bochum, Germany, in 1975.

From 1969 to 1975, he was a Research Assistant at the University of Bochum, where he was involved with electromagnetic theory and numerical methods for solving field problems. From 1976 to 1983, he was a Senior Research Engineer conducting research on direct and inverse scattering problems, imaging with electromagnetic waves with synthetic aperture methods, and industrial applications of microwave techniques. Since 1983, he has been a Professor of microwave techniques at University of Wuppertal, Wuppertal, Germany. His current research activities include microwave system applications of HTS's in field communication and sensing, as well as the theory and practical realization aspects of small arrays with adaptive beamforming capabilities. In the field of microwave superconductivity applications, he is cooperating with the spin-off company Cryoelectra GmbH, Wuppertal, Germany, which provides cryogenic microwave components and subsystems for mobile communication base-stations and navigation systems.

Dr. Chaloupka is a senior member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) 18 Committee on Microwave Superconductor Applications.

Serguei Kolesov received the diploma degree in electronics and the candidate of Sc. degree (Ph.D.) in radio physics from the Electrotechnical University of St. Petersburg, St. Petersburg, Russia, in 1979 and 1986, respectively.

From 1979 to 1994, he was a Research Fellow at the Electrotechnical University. In 1995, he joined the Microwave Technology Group, University of Wuppertal, Wuppertal, Germany, where he has been involved in investigations of the nonlinear behavior of superconductors at microwave frequencies and at high microwave power level. His research was later concentrated on the applications of HTS films in high-power filters for OMUX's of communication satellites and output combiners of mobile communication base-stations. Since 2000, he has been with Cryoelectra GmbH, Wuppertal, Germany, where he is involved in the development HTS resonators and filters to be used in mobile communication systems.

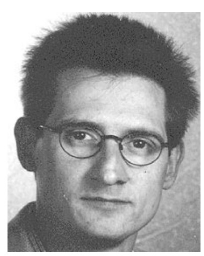
Helmut Piel received the Dr. rer. nat. degree in physics from the University of Bonn, Bonn, Germany, in 1966.

From 1965 to 1970, he was a Research Assistant in the Physics Department, Bonn University. After a two-year fellowship for experimental research work on deep inelastic electron nucleon scattering at the Stanford Linear Accelerator Center (1970–1971), he returned to Bonn University, where he began research on RF superconductivity and accelerator physics. After his "Habilitation," in 1973, he became a Full Professor at the University of Wuppertal, Wuppertal, Germany. His primary research work since 1972 has focused on the study of superconductivity materials in time-dependent electromagnetic fields with the goal of applying superconductivity cavities in high-energy accelerators and paving the way for their use in experimental physics and microwave technology. In 1979, he spent a sabbatical year at European Organization for Nuclear Science (CERN), Geneva, Switzerland. Since 1986, he has been a Distinguished Visiting Professor at the College of William and Mary, Williamsburg, VA. In 1992, he (with support from 12 senior scientists of Germany and the U.S.), co-founded Cryoelectra GmbH, Wuppertal, Germany, which is devoted to the development and marketing of HTS components for communication and power technologies.

Dr. Piel was a member of the Scientific Council of Deutsches Elektronen-Synchrotron (DESY), a scientific advisor of the Director General of CERN, and a member of the National Advisory Board of the Continuous Electron Beam Accelerator Facility (CEBAF). In 1986, he received a prize for achievement in accelerator physics and technology, presented by the U.S. Particle Accelerator School.

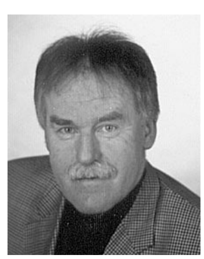
Norbert Klein received the diploma and Ph.D. degrees in physics from the University of Wuppertal, Wuppertal, Germany, in 1985 and 1989, respectively.

From 1990 to April 1999, he was with the Jülich Research Centre, Jülich, Germany, as Head of a group engaged in the exploration of the microwave properties of superconductors and dielectric materials, dielectric filters, and low-phase-noise microwave oscillators. Since May 1999, he has been a Division Leader for superconducting electronics at the Institute of Thin Film and Ion Technology, Jülich Research Centre, Jülich, Germany. He is also a Lecturer at the Technical University of Aachen, Aachen, Germany, in 1998.



Stefan Schornstein was born in Mayen, Germany, on March 18, 1966. He received the diploma degree in physics from the Technical University of Aachen, Aachen, Germany, in 1996.

He spent two years at the Research Center, Jülich, Germany, involved with HTS shielded high-power dielectric dual-mode filters. He is currently a Manager–Consultant in telecommunications.



Martin Bareiss was born July 3, 1946. He received the Dipl.-Ing. degree in aircraft and spacecraft engineering from the University of Stuttgart, Stuttgart, Germany, and the Ph.D. degree in thermodynamics and heat transfer from the University of Darmstadt, Darmstadt, Germany.

Before joining the Cryogenics Department, AEG, in 1985, he spent four years at Battelle, Frankfurt, Germany, where he managed energy and process engineering projects. At AEG Infrared Module GmbH (AIN4), he was in charge of research, development, and production of miniature cryocoolers for IR and HTS applications. Since 1995, he has been a Professor of thermodynamics in the Department of Mechanical Engineering, University of Paderborn, Soest, Germany.