An all-cryogenic low phase-noise hybrid K-band oscillator for satellite communications

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***ABSTRACT* — Within the frame of the German research programme „High-temperature superconductor systems for satellite communication", a low phase-noise K-band oscillator, based on space qualified technology, materials and parts, has been developed. Our approach is an all-cryogenic hybrid oscillator based on a sapphire whispering-gallery mode resonator and a low-noise PHEMT amplifier. Despite the simple concept of the oscillator, phase noise values superior to quartz stabilized oscillators operating at the same frequency have been achieved. In addition to low phase noise, the oscillator possesses mechanical and electrical frequency tunability. This type of oscillator shows potential to greatly enhance the performance of the carrier frequency generation in future satellite payloads.**

I. Introduction

Low-phase noise oscillators are considered to be key components in advanced microwave systems, as e.g. in future onboard processing satellites that use K-band frequencies. A few years ago, the investigation of HTS (high-temperature superconductor) technology for space applications began and with the rise of possible cryogenic payloads, oscillators composed of resonators made from HTS or cooled low-loss dielectrics became an interesting topic [1].

The chance to enhance the performance of simple oscillators was given by the very high *Q*-values achievable at cryogenic temperatures. In addition, the choice of a suitable active element is of equal importance.

The lowest microwave amplifier phase noise values reported so far for conventional field-effect (FETs) and high-electron mobility field effect transistors (HEMTs) based on III/V semiconductors are about –130 dBc/Hz at 1 kHz frequency offset from a carrier frequency of about 10 GHz [2]. Even lower values of the 1/*f* noise have been reported for HBTs [3]. Another very promising new development are HEMTs based on gallium nitride (AlGaN-HEMTs) with high-frequency gain and phase noise performance apparently being superior to gallium arsenide and indium phosphide HEMTs [4]. However, such semiconductors for K-band amplifiers are not yet available for space applications.

In order to achieve an oscillator phase noise close to that of the amplifier for frequency offsets of one kilohertz, extremely high resonator quality factors are required. Employing the Leeson formula [5] loaded *Q*-values in the range of 10^7 were found to be necessary. Whispering-gallery (WG) modes in cryogenically cooled low-loss dielectrics have the potential to fulfil this requirement.

WG modes are modes with high azimuthal mode number *m* in dielectric cylinders. In case of high-purity sapphire as resonator material WG modes allow for the highest unloaded *Q*-values above liquid helium temperature, which are close to that of superconducting niobium cavities. This is due to the low values of the loss tangent of sapphire which drops almost proportional to T^5 from $7\cdot10^{-6}$ at room temperature to $6\cdot10^{-8}$ at 77 K for f = 10 GHz [6]. For $m \geq 7$ the loss contribution of the embedding metallic housing becomes negligible and *Q*-values in the 10^7 range become possible at temperatures of 50 – 80 K, which are accessible with low-power cryocoolers. An addition to high *Q*-values, the strong field confinement inside the sapphire cylinder and the high mechanical stability of sapphire make sapphire WG mode resonators attractive to be used as frequency stabilizing elements in microwave circuits. Drawbacks of WG modes are the relatively large mode density, their dual-mode character and the high temperature coefficient of the resonant frequency of about 40 ppm/K at T = 77K (see II and III).

Beyond the simple feedback oscillator topology, oscillator phase noise values below that of a free-running oscillator can be achieved by combining a phase-locked-loop (PLL) circuit with a feedback oscillator circuit. For such an assembly a high-*Q* resonator is employed as phase discriminator, which allows for compensation of phase fluctuations by the amplifier [2,7]. Using this technique, phase noise values as low as –140 dBc/Hz at 1 kHz frequency offset from a carrier frequency of about 10 GHz have been reported for a Peltier cooled WG resonator with *Q* of only

200.000 [7]. However, such oscillators are quite bulky and complex because of the additional microwave components.

II. Oscillator Design And Assembly

We performed a prototype design study for an all-cryogenic loop oscillator for future on-board satellite application. The key specifications were defined in accordance with this application potential:

1. Precise setting of the oscillator frequency
2. Electrical tunability for implementing the oscillator in a PLL and for electronic compensation of frequency fluctuations occurring during operation on a cryogenic platform.
3. Demonstration of operation on a cryogenic platform to be held at a temperature of $T = (77 \pm 0.1)$ K employing a low-power Stirling-type cryocooler.
4. Construction of a space qualifiable and light-weight oscillator assembly of simple structure.
5. Phase noise below that of multiplied quartz oscillators.

The first prototype oscillator we built is shown in Fig. 1. In our approach, a modular setup has been selected in order to be able to characterize each component individually. First, the properties and performance of the components will be discussed:

Resonator : We have constructed a sapphire dielectric resonator excited in a WG mode with azimuthal order $m = 7$. Tuning of the resonance frequency was accomplished by changing the physical distance between the sapphire resonator and a sapphire tuning disk. A mechanical tuning screw with a special spring-washer arrangement has been developed. The total tuning range was found to be 50 MHz with an adjustment accuracy of less than 50 kHz. For electromechanical tuning a stack of multilayer piezoelectric transducers has been employed for lifting the spring-like metallic bottom plate of the resonator housing. Thus the sapphire cylinder, which is soldered to the bottom plate, can be moved upwards with respect to the tuning disk. After optimization, we have attained a maximum tuning range of 50 kHz for a voltage change of 60 V applied to the piezoelectric transducers (Fig. 2). The highest loaded Q-value of the resonator was found to be $3{\cdot}10^6$ at 77 K for a resonator insertion loss of -7dB. From the coupling coefficient the unloaded Q was determined to be $6{\cdot}10^6$. From literature data [6] the loss tangent of sapphire is expected to be $(7.2{\cdot}10^6)^{-1}$ indicating that our resonator design allows for Q-values very close to the fundamental limits of quantum absorption by phonons.

Over the entire mechanical tuning range of 50 MHz the unloaded Q-value was found to be above $2{\cdot}10^6$. The tuning behavior was simulated numerically employing a finite difference field simulation technique.

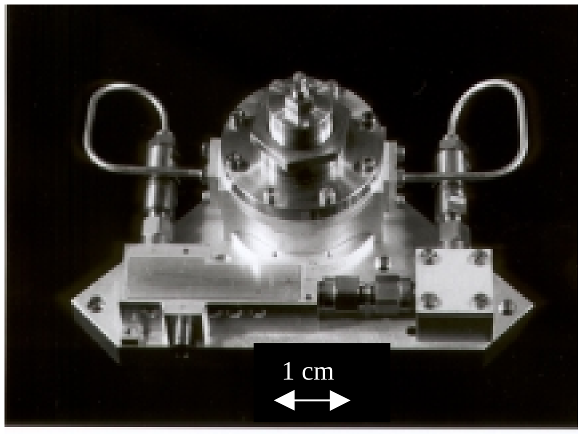

Fig.1. Photograph of the cryogenic 23 GHz prototype oscillator consisting of a whispering-gallery mode resonator (large circular metal housing), a 2-stage PHEMT-amplifier (rectangular housing) and a high-temperature superconducting bandpass filter for mode selection (square housing).

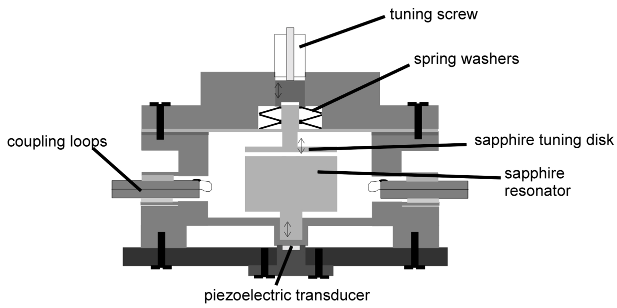

Fig.2. Tunable whispering-gallery mode resonator for $f = 23$ GHz with mechanical / piezomechanical tuning range of 60 MHz / 50 kHz.

Amplifier: In the early development phase, several microwave FETs and HEMTs were tested and preselected with respect to low $1/f$ – noise and high amplification. Based on the choice of a space qualified PHEMT, a cryogenic two-stage amplifier including a varactor phase shifter and a 3 dB output coupler has been developed. The insertion gain is 11 dB, the maximum phase shift was found to be 70 degree.

Filter: A HTS two-pole dual-mode bandpass filter, which avoids locking to any spurious mode, was designed and built. For a relative bandwidth of 1% the insertion loss was found to be 1 dB.

Two identical oscillators have been assembled and tested. The phase-condition for self oscillation was achieved by use of semi rigid cables of correct physical length. The resonator coupling was adjusted for an insertion loss about 6 dB, resulting in loaded *Q*-values above 10^6.

III. MEASURED OSCILLATOR PERFORMANCE

Two identical oscillators were tested by operating both inside one vacuum dewar. Cooling to liquid nitrogen temperature was attained by mounting the oscillators onto the copper bottom plate of the dewar. The bottom plate was cooled from the outside with liquid nitrogen. Temperature controlling for each oscillator was provided by employing a temperature sensor and a heat resistor in connection with a Lake Shore temperature controller.

The temperature coefficient of the resonator frequency was determined to be 40 ppm / K at 77 K corresponding to the expected temperature dependence of the permittivity of sapphire. Thus the electrical tuning range is high enough to compensate for temperature fluctuations up to 50 mK. Such temperature stability should be easily achievable on a cryogenic platform in a satellite.

The WG-modes in cylindrical dielectric resonators are dual-modes corresponding to waves propagating along the circumference of the sapphire cylinder in a clock or counterclockwise direction, respectively. As a result of deviations from the ideal cylindrical symmetry, e.g. due to coupling loops, we observed a splitting of each WG resonance in two distinct modes separated from each other by about 60 to 150 kHz. Since the coupling to both modes is of similar strength, the oscillator can either operate at one or another resonant frequency depending on the phase condition within the feedback loop and therefore on the voltage applied to the varactor phase shifter. Currently, a modified resonator design which avoids two equally coupled WG modes with such a small difference in resonance frequency is under development.

Phase noise measurements were performed by the use of a HP phase noise measurement setup. Since the phase noise of our oscillator is lower than that of all available K-band sources, two oscillators were mixed to an intermediate frequency and the phase noise of this signal was measured against a quartz reference.

The amplifier's residual phase noise was determined using the same driving level as the one occurring in the oscillator. According to the results shown in Fig. 3, the amplifier phase noise exhibits an almost ideal $1/f$ dependence at T = 77K with an absolute value of

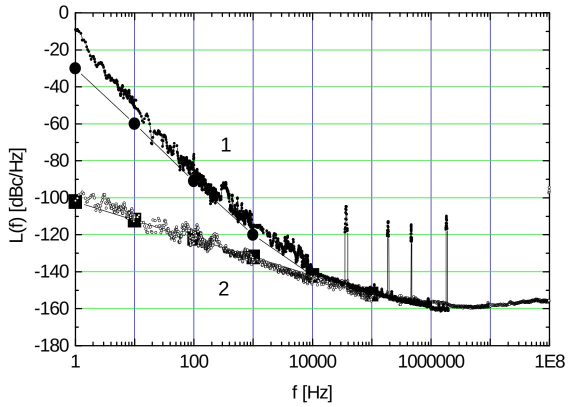

Fig.3. Measured phase noise of the amplifier (2) and of the oscillator (1). The squares represent a $1/f$ fit to the amplifier noise, the circles represent the oscillator phase noise calculated from the fit to the amplifier phase noise according to the Leeson formula.

–133 dBc/Hz at a frequency offset of 1 kHz, which is nearly independent of the value of the gate source voltage U_{GS} applied to the transistors. In contrast, at 300 K we observed some U_{GS} dependent deviations from the $1/f$ behavior, which result in phase noise values being more than 3 dB higher.

The oscillator phase noise depicted in Fig. 3 corresponds to the measured noise minus 3dB, assuming that both oscillators have the same performance. The measured values are still slightly above the values predicted by the Leeson formula for frequency offsets below 10 kHz (circles in Fig. 3). This discrepancy is still not fully understood. In spite of this, to the best of our knowledge, this is the best performance ever published for a K - band oscillator (see e.g. [8]).

IV. ONBOARD APPLICATION

Up to now, there is a continuing discussion about the economic advantages of onboard cryogenic communication equipment in satellites. The not-yet-answered question is whether cryogenic payloads will become state-of-the-art in future communication satellites [1] or whether the use of cryogenic systems in space will be restricted to a few cases where the highest possible performance is required and paid for.

As the most important issue, a new optimised cryogenic payload concept has to be found. The components that were considered mostly in the past were front-ends with low-noise amplifiers (LNAs) as well as input and output multiplexers consisting of HTS or cooled dielectric filters. The possible use of a high performance oscillator like the one discussed below offers additional benefits:

• Since our oscillator is able to offer a long term frequency stability in the range of $4x10^{-8}$ when temperature is tightly controlled , there is no longer need for a 10 MHz master oscillator. Such an oven controlled crystal oscillator (OCXO) has a power consumption of 3-5 W and a long term stability of $3{\cdot}10^{-8}$. In addition, several microwave oscillators which are phase locked to this reference source have to be implemented. Their power consumption is about of 1-2 W. Assuming that the COP (coefficient of power) of the cryocooler is 5% [1], the additional dc power needed for the cooling of our oscillator is 1.6 W due to the amplifier power consumption of 80 mW. Thus there is a saving of at least 3 W with respect to a conventional system. It should be emphasised that this analysis is based on the assumption that the oscillator is implemented on an already existing cryoplatform, i.e. additional heat load by radiation and microwave connectors are neglected.

• Furthermore, the phase noise performance is much better than that of a conventional phase locked oscillator (Fig.4). As already claimed, our performance has not been surpassed at K-band frequencies [8].

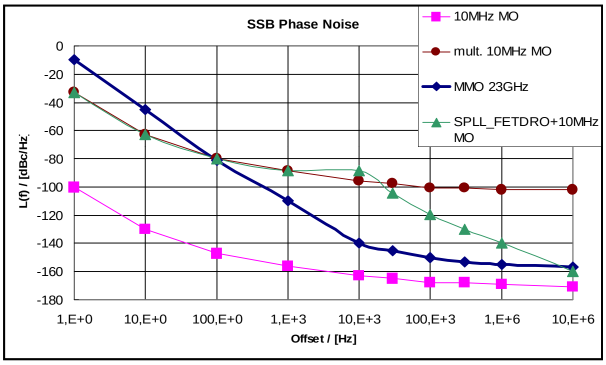

Fig.4. Phase noise of our 23GHz oscillator (diamonds) in comparison to that of a multiplied 10 MHz master oscillator (MO, squares), a FETDRO (FET-based dielectric resonator oscillator, triangles) being phase locked to the same MO, and a multiplied quartz oscillator (circles).

• In future on-board-processing satellite systems, there will be a need for a highly flexible and high performance carrier generation within the K-band. A microwave master oscillator (MMO) like the one built could pave the way for a LO generation scheme employing digital phase-locked loops (DPLLs) at frequencies in the 1-3 GHz range together with frequency upconversion by the MMO. The reference frequency for such DPLLs would become variable by tuning of the MMO and by selection of different division factors. With such a system, the performance and flexibility of an S-Band synthesizer could become available at K-band frequencies.

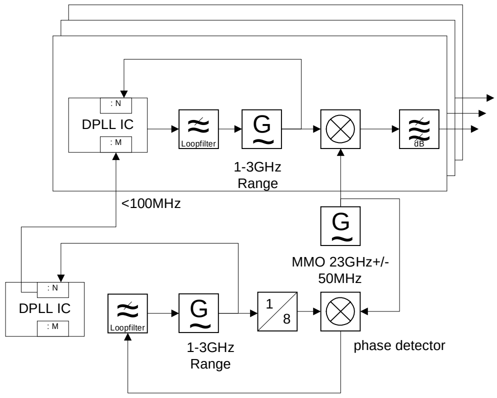

Fig.5. Example of a flexible frequency generation system for K-band on-board processing satellites.

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