Design and Characterization of an All-Cryogenic Low Phase-Noise Sapphire K-Band Oscillator for Satellite Communication

Svetlana A. Vitusevich, Klaus Schieber, Indra S. Ghosh, Norbert Klein, and Matthias Spinnler

***Abstract*—An all-cryogenic oscillator consisting of a frequency-tunable sapphire resonator, a high-temperature superconducting filter and a pseudomorphic high electron-mobility transistor amplifier was designed for the K-band frequency range and investigated. Due to the high quality factor of the resonator above 1 000 000 and the low amplifier phase noise of approximately −133 dBc/Hz at a frequency offset of 1 kHz from the carrier, we have achieved oscillator phase-noise values superior to quartz-stabilized oscillators at the same carrier frequency for offset frequencies higher than 100 Hz. In addition to low phase noise, our prototype oscillator possesses mechanical and electrical frequency tunability. We have implemented a two-step electrical tuning arrangement consisting of a varactor phase shifter integrated within the amplifier circuit (fine tuning by 5 kHz) and a dielectric plunger moved by a piezomechanical transducer inside the resonator housing (course tuning by 50 kHz). This tuning range is sufficient for phase locking and for electronic compensation of temperature drifts occurring during operation of the device employing a miniaturized closed-cycle Stirling-type cryocooler.**

***Index Terms*—Dielectric resonator oscillator, oscillator noise, phase noise, satellite communication.**

I. Introduction

LOW phase-noise oscillators are considered to be key components for advanced microwave communication, radar, and measurement systems. As an example, in future on-board processing satellite systems, there is a need for a high-performance carrier generation at K-band frequencies. As a possible system approach, flexible local oscillator (LO) generation schemes employing digital phase-locked loops (DPLLs) at frequencies from 1 to 3 GHz can be used in combination with up- or down-conversion through a very low phase-noise LO. With such a system, the performance and flexibility of an S-band synthesizer should become available at K-band frequencies if the oscillator phase-noise performance is superior to quartz-stabilized references.

A few years ago, the investigation of high-temperature superconducting (HTS) 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 thus far for conventional field-effect transistors (FETs) and high electron-mobility transistors (HEMTs) based on III–V semiconductors are approximately −130 dBc/Hz at 1-kHz frequency offset from a carrier frequency of approximately 10 GHz [2]. Even lower values of the $1/f$ noise have been reported for heterojunction bipolar transistors (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], [5]. However, such semiconductors for K-band amplifiers are not yet available for space applications.

As the most simple and versatile oscillator approach, the output signal of a low $1/f$-noise microwave amplifier is passed through a two-port microwave resonator and fed back to the amplifier input. If the total phase shift around the oscillator loop is an integer of 2π and the total loop amplification (equal to amplifier gain minus insertion loss of resonator and other components) exceeds unity, this device oscillates at one of the resonant frequencies of the resonator. The basic phase-noise behavior of the oscillator circuit is described by the Leeson model [6], which is based on the properties of the oscillator components. Phase noise of the amplifier is translated into oscillator phase noise according to the following:

$$L_{\rm osc} = 10\cdot\log\left[1+\frac{f_0^2}{4Q_L^2 f_m^2}\right]+10\cdot\log\left[\frac{\alpha}{f_m}+\frac{GFkT}{P}\right]. \quad (1)$$

The second term in (1) represents the amplifier noise consisting of white noise determined by the amplifier gain G, its noise figure F, its physical temperature T, and its output power P. In addition, there is $1/f$ noise leading to a fluctuation amplitude α/f_m at a frequency distance $\pm f_m$ from the carrier frequency f_0. The first term in (1) represents the resonator noise amplification factor, which is 3 dB for $f_m = (1/2)\Delta f_{1/2} (\Delta f_{1/2} = f_0/Q_L)$, and increases strongly for lower offset frequencies. According to (1), the oscillator phase noise exhibits a $1/f_m^3$ dependence in a certain range

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of offset frequencies. This noise decreases strongly upon increasing the loaded quality factor Q_L of the resonator.

According to (1), the lowest possible oscillator phase noise ($Q_L \rightarrow \infty$) is determined by the phase noise of the amplifier. In order to achieve an oscillator phase noise close to that of the amplifier for frequencies offsets of 1 kHz, extremely high resonator quality factors are required. Employing the above-mentioned 3-dB criterion according to (1), for a frequency offset of $f_m = 1$ kHz, the required loaded quality factor is $1.1 \cdot 10^7$. Whispering-gallery (WG) modes are modes with high azimuthal mode number m in dielectric cylinders. In the case of high-purity sapphire as the resonator material, WG modes allow for the highest unloaded quality factors 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 $7 \cdot 10^{-6}$ at room temperature to $6 \cdot 10^{-8}$ at 77 K for $f = 10$ GHz [7]. For $m \geq 7$, the loss contribution of the 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 approximately 40 ppm/K at $T = 77$ K (see Sections II and III).

Beyond the simple feedback oscillator topology, oscillator phase-noise values below that predicted by (1) 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 a 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 approximately 10 GHz have been reported for a Peltier cooled WG resonator with Q of only 200 000 [8]. However, such oscillators are quite bulky because the PLL circuit is composed of discrete components.

II. Oscillator Design and Assembly

As our own approach, we have performed a prototype design study for an all-cryogenic loop oscillator with phase noise determined by (1) for future on-board satellite application. The key specifications were defined in accordance with the following application potential:

1) precise setting of the oscillator frequency a $f = 23\,000\,000$ kHz;
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 $T = (77 \pm 0.025)$ K employing a low-power Stirling-type cryocooler;
4) construction of a space qualified and lightweight oscillator assembly;
5) phase noise below that of multiplied quartz oscillators.

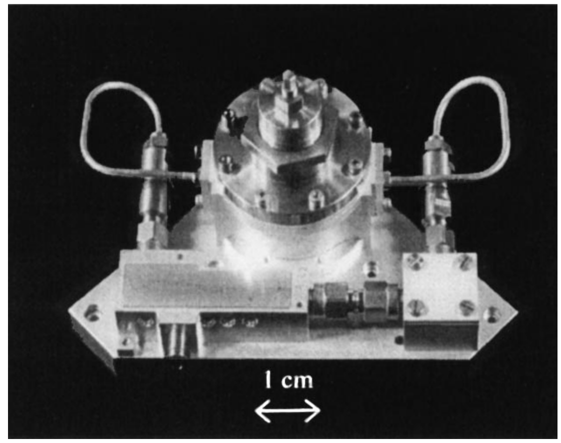

Fig. 1. Photograph of the cryogenic 23-GHz prototype oscillator consisting of a WG-mode resonator (large circular metal housing), a two-stage HEMT amplifier (rectangular housing), and an HTS bandpass filter for mode selection (square housing).

The first prototype oscillator we have built is shown in Fig. 1. As a first approach, we have selected a modular setup 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. The main disadvantage of WG resonators is the high spurious-mode density. The mode spectrum was, therefore, calculated employing the computer code MAFIA [9]. The electromagnetic-field confinement increases as a function of the WG-mode number at the same time the mode density including empty cavity modes perturbed by the sapphire cylinder becomes higher. Therefore, the seventh WG mode corresponding to 14 maxima of the electromagnetic-field energy along the circumference was used as a compromise between Q and the mode density (Fig. 2).

A WG-mode sapphire resonator has been designed based on a sapphire cylinder with 13 mm in diameter and 5 mm in height. For measurements, the cylinder was centered in a silver-plated oxygen-free high-conductivity (OFHC) cylindrical copper cavity and fixed by soldering. Tuning of the resonance frequency was accomplished by changing the physical distance between the sapphire resonator and a sapphire tuning disk (Fig. 3).

The tuning behavior was simulated numerically employing a finite-difference field-simulation technique. Table I shows the calculated resonance frequencies for a frequency range of 23.03±0.50 GHz and two settings of the sapphire tuning disk (where d is the distance between the sapphire cylinder and tuning disk).

According to Table I, the WG (WGH_{700}) mode represents a higher order mode with a high density of spurious modes around. In the WG mode, most of the electromagnetic energy is confined inside the dielectric. Therefore, the perturbation of the cavity geometry due to the coupling antennas is insignificant.

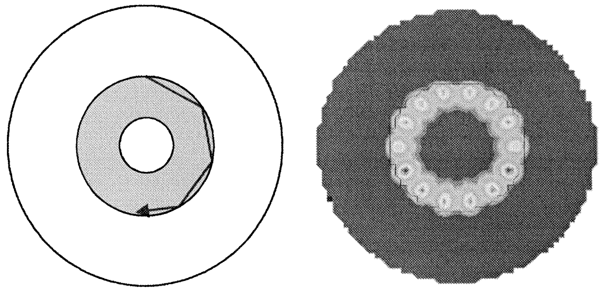

Fig. 2. Basic concept and numerically calculated distribution of electric-field energy of a WG resonance with $m = 7$.

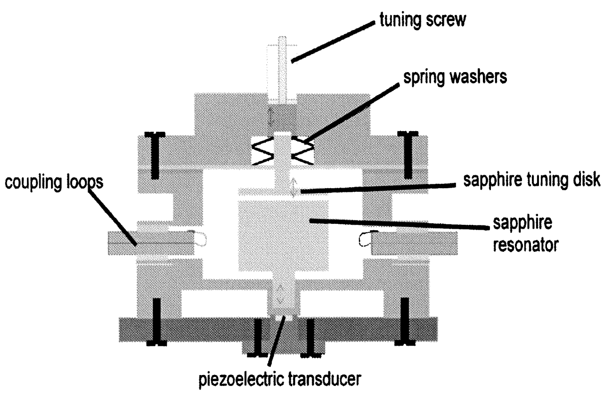

Fig. 3. Tunable WG-mode resonator for $f = 23$ GHz with mechanical/piezomechanical tuning range of 60 MHz/50 kHz.

TABLE I
CALCULATED RESONANCE FREQUENCIES FOR A FREQUENCY RANGE OF 23.03±0.50 GHz

Azimuthal mode number	Frequency (GHz) d = 1 mm	Frequency (GHz) d = 2 mm
TE n = 0	-	23. 345
TM n = 0	-	-
Hybrid mode (HM) n = 1	22. 764 23. 326	23. 272 23. 356
HM n = 2	23. 115	23. 136
HM n = 3	23. 276	23. 291
HM n = 4	22. 864 23. 291	22. 951 23. 379
HM n = 5	-	-
HM n = 6	-	-
HM n = 7 (WGH_{700})	23. 025	23. 034

We have developed a mechanical tuning screw with a special spring-washer arrangement. For electrical tuning, we have employed a stack of multilayer piezoelectric transducers 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 disc.

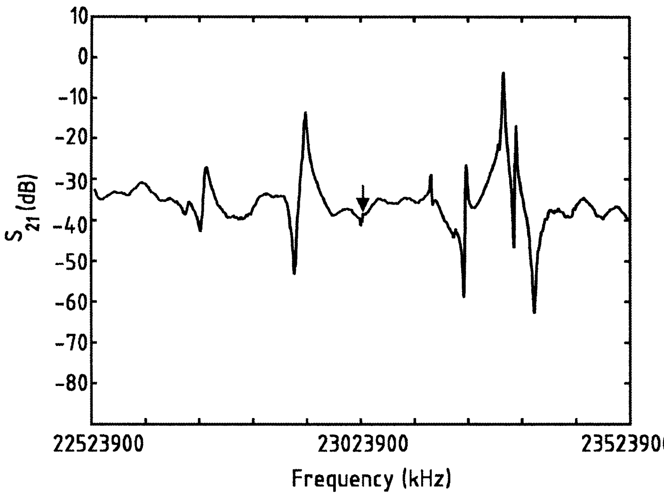

Fig. 4. Spectrum of 23-GHz resonator at $T = 78$ K measured with 1-GHz frequency span.

Over the entire mechanical tuning range of 50 MHz, the unloaded quality factor of the resonator was found to be above $2 \cdot 10^6$.

A typical resonator spectrum measured at 78 K is shown in Fig. 4. The peak of the WG mode is not fully represented due to the very small bandwidth of the resonance (very high-Q factor) and the limited resolution of the analyzer. According to Fig. 4, the WG mode does not overlap with other modes, but the minimum distance to the next spurious mode is only 100 MHz (see also Table I). The loaded quality factor was determined to be $3.2 \cdot 10^6$, indicating that our resonator design allows for Q values very close to the fundamental limits of quantum absorption by phonons [10].

The coupling coefficient was determined to be 0.4 for both ports resulting in a ratio of unloaded to loaded quality factor of 1.8. Accordingly to [11], this value represents an optimum with respect to low phase noise.

The WG modes (Fig. 5) 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 approximately 60–150 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.

The total mechanical tuning range was found to be 50 MHz with an adjustment accuracy of 50 kHz. After optimization, we have attained a maximum tuning range of 50 kHz for a voltage of 60 V applied to the piezoelectric transducers.

Amplifier: Several commercial high-frequency FETs and HEMTs were tested and preselected with respect to low $1/f$ noise and high amplification. An AlGaAs/InGaAs/GaAs pseudomorphic high electron-mobility transistor (pHEMT)

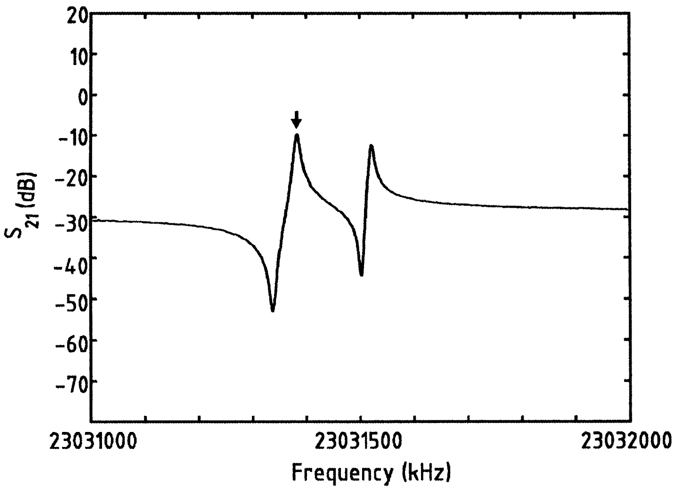

Fig. 5. Spectrum of 23-GHz resonator at $T = 78$ K measured with 1-MHz span.

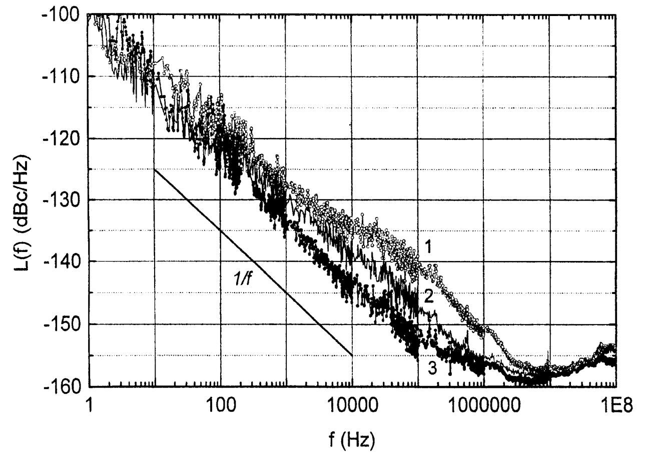

Fig. 6. Measured phase noise of the amplifier. (1) $T = 300$ K, $U_{\rm SG} = -0.4$ V. (2) $T = 300$ K, $U_{\rm SG} = -0.8$ V. (3) $T = 77$ K, $U_{\rm SG} = -0.4$ V and $U_{\rm SG} = -0.8$ V.

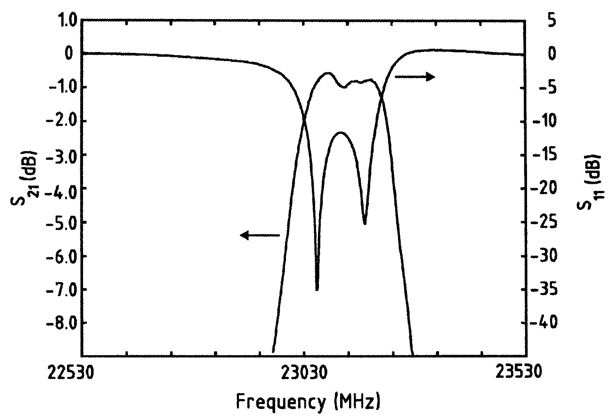

Fig. 7. Measured HTS filter response. S_{11}: reflected signal. S_{21}: transmitted signal.

was selected for two-stage amplifier design. We have developed a cryogenic two-stage HEMT amplifier including a semiconductor varactor phase shifter and a 10-dB output coupler. On-wafer measured S-parameters served as input data for a hybrid microstrip design. Two-step amplification has been optimized for setting the gain a little bit higher than the insertion loss of the oscillator loop, including resonator, filter, and coaxial coupling loops. As total gain, we have achieved a value of 11 dB, the maximum phase shift was found to be 70°.

The amplifier phase noise was measured in a two-branch configuration employing an HP phase-noise measurement system: a continuous wave (CW) signal at 23 GHz generated by an HP 83640A synthesized sweeper is split into two equal parts, one passing through a phase shifter, the other through the amplifier. When the phase difference is adjusted to 90° (quadrature), the output voltage is zero. Therefore, any phase fluctuation of the amplifier can be registered as a voltage fluctuation at the output. The measurements were carried out for the onset of the saturation regime of the amplifier at source–drain voltage $V_{\rm SD} = 2$ V.

The measured amplifier phase-noise results are shown in Fig. 6. It can be seen that the intrinsic excess noise is $1/f$ flicker noise plus a small Lorentzian-shaped generation–recombination (g–r) noise. At room temperature, a strong dependence on the gate voltage $U_{\rm SG}$ (curves 1 and 2 in Fig. 6) was observed in comparison to a negligible dependence on the varactor voltage (not shown here). At high negative gate bias, the g–r component of excess noise became smaller and the total level of noise decreases. Decreasing temperature results in a slight reduction of $1/f$ phase noise.

In contrast to room temperature, the noise at 77 K did not show a noticeable dependence on the gate and varactor bias. The phase noise decreases by approximately 1 dBc/Hz with increasing gate voltage from -0.4 to -0.8 V and increasing approximately 2 dBc/Hz with increasing varactor voltage from 0 to 12 V. At a temperature of 77 K, the amplifier phase noise exhibits an almost ideal $1/f$ dependence. The best phase-noise level for the 23-GHz amplifier was determined to be -133 dBc/Hz at 1-kHz offset from the carrier frequency.

Filter: We have constructed an HTS two-pole dual-mode bandpass filter, which avoids locking to any spurious mode.

The HTS filter has a center frequency of approximately 23 GHz, the width of the passband is 140 MHz. The center frequency can be varied over 200 MHz by employing different covers for the filter housing. Fig. 7 shows the HTS filter response at 1-GHz frequency span. For frequencies within the passband, the filter exhibits an insertion loss of approximately 1 dB. Our experiments indicate that this filter provides a sufficient suppression of spurious mode locking close to the WG mode. Without this filter, we have not been able to lock the oscillator to the WG mode.

III. Measured Oscillator Performance

If the total phase shift around the oscillator loop is an integer multiple of 2π and if the HTS filter is tuned correctly to avoid locking to any spurious mode, the device oscillates at a frequency corresponding to the resonant frequency of the WG mode. According to Fig. 8, a clear output spectrum at 23 GHz was demonstrated. The measurements were taken with a drain bias of 2 V, a gate bias of -0.6 V, and a varactor bias of 9 V. A maximum output power of 7 dBm was measured for on oscillator assembly with optimum setting of the oscillator frequency with respect to the HTS filter passband. Two identical oscillators

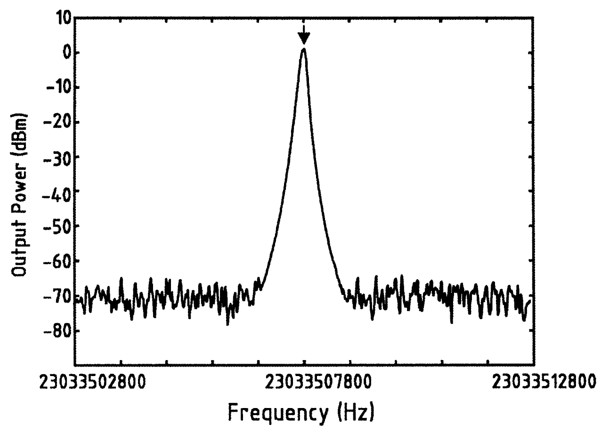

Fig. 8. Output power spectrum of the 23-GHz oscillator.

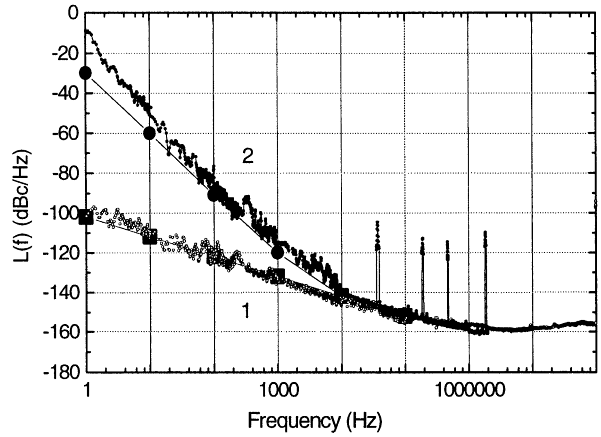

Fig. 9. Measured phase noise: (1) of the amplifier and (2) of the oscillator. Squares: $1/f$ fit to the amplifier noise. Circles: oscillator phase noise calculated from the fit to the amplifier phase noise according to the Leeson formula.

have been assembled and tested. The 2π condition for self-oscillation was achieved by subsequent tests employing semirigid connecting cables of different physical length. The resonator coupling loops were adjusted to attain a suitable compromise between sufficiently high loaded Q value and sufficiently low resonator insertion loss. Typically, the insertion loss was adjusted to be approximately 6 dB, resulting in loaded Q values above 10^6.

Since the phase noise of our oscillator is lower than that of all commercially available K-band sources, two oscillator were mixed to an intermediate frequency and 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 carrier frequency of the two assembled resonators are set to be approximately 23 GHz with a frequency difference between them of nearly 10 MHz. The signals of two oscillators were directed to a mixer. The mixed signal was applied to the input of the phase-noise system.

The beat signal is measured against the reference signal created by the HP 8662 microwave synthesizer adjusted to the lowest specified noise level at a carrier frequency of 320 MHz. The required 10-MHz signal was generated employing a low-noise frequency divider (division by 32). The temperature was stabilized at 78 K using a Lake–Shore temperature controller with a silicon diode temperature sensor and a heat resistor. The achieved temperature stability was approximately ± 3 mK.

Measured and calculated phase-noise results for the amplifier and oscillator are shown in Fig. 9. The amplifier phase noise exhibits an almost ideal $1/f$ dependence at $T = 77$ K with an absolute value of -133 dBc/Hz at a frequency offset of 1 kHz, which is nearly independent on the value of the source gate voltage U_{SG} applied to the transistors. The oscillator phase noise depicted in Fig. 9 corresponds to the measured noise minus 3 dB, assuming that both oscillators have the same performance. The 30 dB per decade region of the $L(f)$ curve was fitted with the empirical relation of the Leeson model. The value of the phase noise is -118 dBc/Hz at 1 kHz and is superior to any commercial K-band oscillator.

The measured values are still slightly above the values predicted by the Leeson formula for frequency offsets below 10 kHz (circles in Fig. 9). 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., [12]).

For modern telecommunication system, the important offset frequency range of oscillator phase noise is above 1 kHz since it strongly influences the phase modulation of the system. Any variation in gate-bias voltage of the amplifier results in pushing the oscillator phase noise upwards. The sensitivity of the carrier frequency with respect to the gate bias can be characterized by the up-conversion factor [13]. Usually the up-conversion factor of oscillators is approximately 3 MHz/V for an offset frequency of 1 kHz. Our estimation based on measured values of phase noise of amplifier and oscillator shows an up-conversion factor of approximately 50 kHz/V for 1-kHz offset frequency. This value demonstrates that, in our oscillator, the nonlinear processes resulting in noise up-conversion are unremarkable.

For frequency offsets above 100 Hz, the achieved phase noise of our oscillator (diamonds in Fig. 10) is below that of commercial sources (circles and triangles), which are usually based on a 10-MHz quartz reference (squares). Therefore, it is worth considering a system implementation of our oscillator in the near future.

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 achievable on a cryogenic platform in a satellite.

IV. On-Board Application

Up to now, there is a continuing discussion about the economic advantages of on-board 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 optimized 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 con-

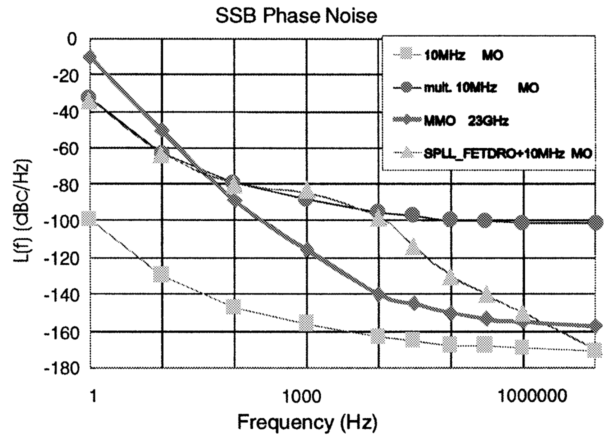

Fig. 10. Phase noise of our oscillator (diamonds) in comparison to that of commercial sources of the same frequency (circles and triangles) based on a 10-MHz quartz reference (squares) (from [12]).

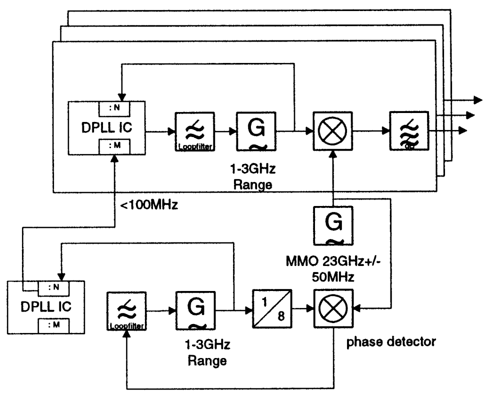

Fig. 11. Example of a flexible frequency generation system for K-band on-board processing satellites.

sisting of HTS or cooled dielectric filters. The possible use of a high-performance oscillator like the one discussed below offers additional benefits:

- As shown in [14], the frequency stability of sapphire WG resonators operated on a cryocooler platform was demonstrated to be in the range of 10^{-8} when the temperature is tightly controlled. In that case, there would no longer be a 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 approximately 1–2 W. Assuming that the coefficient of power (COP) 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's power consumption of 80 mW. Thus, there is a saving of at least 3 W with respect to a conventional system. It should be emphasized 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. 10). As already claimed, our performance has not been surpassed at K-band frequencies [13].
- 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 an LO generation scheme employing DPLLs at frequencies in the 1–3-GHz range together with frequency up-conversion by the MMO. The reference frequency for such DPLLs would become variable by tuning of the MMO (Fig. 11) 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.

V. Conclusion

The phase noise of our cryogenic sapphire K-band oscillator has been measured as a function of gate and varactor biases. The best phase noise of the two-stage pHEMT 23-GHz amplifier was found to be -133 dBc/Hz at 1-kHz frequency offset. This transforms into an oscillator phase noise of only -118 dBc/Hz at 1-kHz offset in case of a cryogenic WG-mode sapphire resonator. This value is superior to quartz-stabilized oscillators at the same frequency. This type of oscillator can be used in high data-rate uplink, downlink, or intersatellite links for future multimedia satellites at K-band frequencies for increased data rates, which are now limited by bit errors due to the oscillator phase noise.

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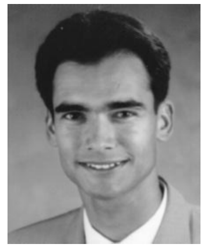

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