Low Noise 9-GHz Sapphire Resonator-Oscillator with Thermoelectric Temperature Stabilization at 300 Kelvin

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Abstract—**This letter reports on an X-band microwave oscillator incorporating a room temperature thermoelectric stabilized sapphire resonator operating at 9.00000 GHz. With a Galani type stabilization scheme we have measured a reduced single sideband phase noise of about −124 dBc/Hz at 1 kHz with a f^{-3} dependence. The measurement was limited by the flicker noise of the phase detector in the feedback electronics. The frequency stability was also measured; at an integration time of 0.1 seconds a $\delta f/f$ of about 10^{-11} with a $\tau^{0.7}$ dependence was measured. The frequency drift strongly correlated with ambient temperature fluctuations.**

I. Introduction

SAPPHIRE resonator technology now provides oscillators at microwave frequencies with performance superior to existing technologies [1]–[5], due to the low dielectric loss tangent of sapphire. Resonator Q-factors at X-band of about 2×10^5 at 300 K, 5×10^7 at 77 K and 8×10^9 at 4 K have been achieved using whispering gallery modes. With the gain in Q-factor the complexity and size of the resonator also increases. For maximum performance liquid helium systems are used. The expense of construction and maintenance of such systems means that they are probably only ever going to be used for special purposes where the best performance is essential. For advanced applications at room temperature, sapphire technology holds a significant advantage at microwave frequencies over other technologies such as YIG and DRO's, and due to its high Qf product potentially has an advantage over quartz based resonators, SAW's and BAW's [6].

II. Thermoelectric Stabilized Resonator

The resonator was designed to operate at 9.0000 GHz with a loaded Q factor of 98,000. Previously we have reported on two other thermoelectric stabilized resonators with center frequencies of 10.000000 GHz and unloaded Q factors of 2×10^5, which are now commercially available [7], [8]. These resonators consist of a cylindrical piece of high-purity single

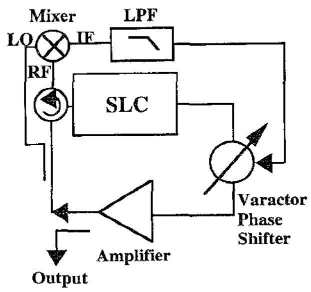

Fig. 1. Schematic of the TE stabilized resonator-oscillator with phase noise cancellation circuitry.

crystal sapphire mounted in a metallic cavity in vacuum. The resonator center frequency and Q factor are determined almost completely by the sapphire. Our design allows the fabrication of resonators to an accuracy of 1 ppm. These resonators are compact and robust and, unlike the cryogenic version, they can easily be used for mobile applications.

The resonator is temperature controlled via a servo which includes a Lock-In Amplifier, PID controller and a thermoelectric (TE) module. Typically at room temperature the thermal time constant is dominated by the sapphire, and can be of the order of 5 minutes [8]. Depending on the power dissipation in the cavity, such long time constants can cause problems with temperature control locking. The thermal time constant of this cavity was specially designed to be just 40 seconds at room temperature. The temperature coefficient of the unlocked cavity was measured to be −70 ppm/K. This is primarily attributable to the temperature coefficient of the sapphire dielectric constant, however we note the thermal expansion also plays a role in determining the magnitude. When we temperature lock the cavity, the sensitivity to ambient temperature is reduced to 0.2 ppm/K.

III. Oscillator Phase Noise Results

A noise reduction technique similar to the methodology describedby Galani *et al.* [9] was implemented. A schematic of the prototype stabilized oscillator is shown in Fig. 1, with a photo shown in Fig. 2. The loop gain characteristics of our noise cancellation was determined mainly by an active filter in the feed back path to the varactor phase shifter. This filter was designed to have maximum gain at 1 kHz.

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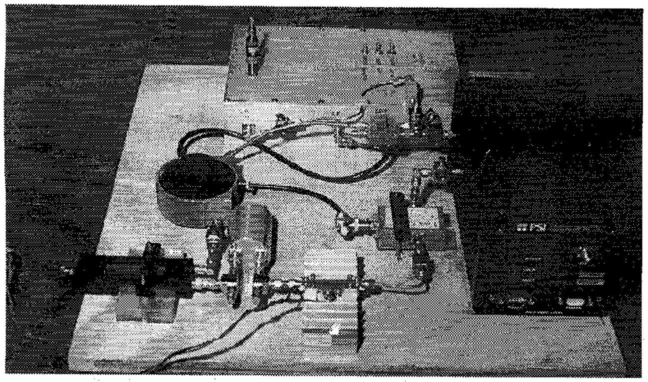

Fig. 2. Photo of the prototype stabilized oscillator. The TE stabilized sapphire resonator from Poseidon Scientific Instruments is the black box on the right. Its dimensions are 21 × 12 × 10.5 cm. The phase servo and feedback electronics are held rigidly on a 47 cm^2 wooden shelf.

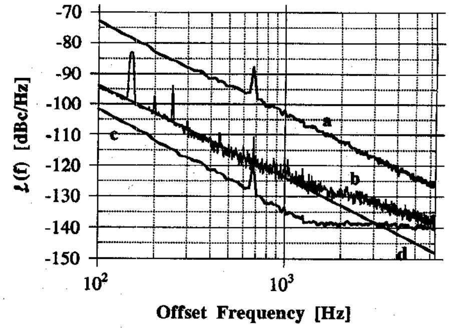

Fig. 3. Measured single sideband phase noise for the TEstabilized sapphire oscillator: (a) open loop configuration; (b) closed loop configuration (below 2 kHz we measured the noise limit due to the phase detector; above 2 kHz we measured noise due to the 8662A synthesizer); (c) open loop noise divided by the loop gain; (d) Oscillator noise limit due to the phase detector.

The reference oscillator for the phase noise measurements was a low noise cryogenic SLOSC oscillator at 9.049 GHz [3] mixed with a 49 MHz signal from an HP 8662A synthesizer. Results reveal an excellent phase noise performance (Fig. 3) of $\mathcal{L}\{100\,\mathrm{Hz}\} = -94$ dBc/Hz and $\mathcal{L}\{1\,\mathrm{kHz}\} = -124$ dBc/Hz. For this measurement we did not require any vibration isolation, which substantiates the fundamentally good performance possible from whispering gallery resonator-oscillators. Above 6 kHz the measured phase noise spectrum was flat out to 100 kHz offset at a value close to -140 dBc/Hz. This noise level is due to the 8662A synthesizer. The noise in the 8662A was determined by beating two separate synthesizers together at 49 MHz and alternating them in the measurement system. Both are fairly old and regularly exhibited phase noise levels above specifications that intermittently changed. Fig. 3 shows results obtained with the best noise floor from one of the 8662A synthesizers. Below 2 kHz offset frequency we have measured the oscillator noise limit due to the voltage noise of the WJ M14A mixer in the phase detector.

IV. Oscillator Frequency Stability

The frequency stability was measured with a HP 8673H microwave synthesizer referenced to a Rubidium frequency standard. This reference oscillator was mixed with the TE stabilized sapphire oscillator creating an 11 kHz beat frequency. A frequency counter interfaced to an Apple Macintosh was used to calculate the frequency deviation of the 11 kHz beat.

Fig. 4 shows two sets of measurements taken between 0.1 and 10 seconds and 10 to 200 seconds integration time. There is a slight jump between the two data sets. At 0.1 seconds we measured a $\delta f/f$ of about 10^{-11} with a $\tau^{0.7}$ dependence. The level of the f^{-3} dependent phase noise corresponds to a flat frequency deviation of $2.6 \cdot 10^{-12}$. We expect to hit this floor for integration times below a few tens of milliseconds. The frequency counter method is not as accurate at smaller integration times, and in this regime the TERP method [10] should be used.

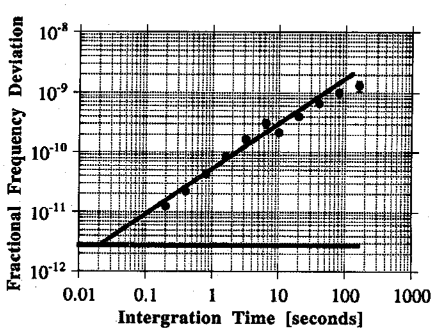

Fig. 4. Allan frequency deviation for the TE stabilized sapphire oscillator. Measured points indicate a $\tau^{0.7}$ dependence. From the measured phase noise we expect the frequency deviation to run into the indicated floor of $2.6 \cdot 10^{-12}$ for smaller integration times.

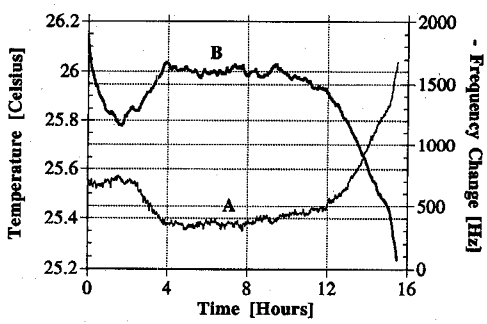

Fig. 5. Curve B shows fluctuations of ambient temperature over 16 hours. Curve A shows the negative change in beat frequency between the reference and sapphire oscillator. The two curves show strong correlation.

Fig. 5 shows how the frequency of the sapphire oscillator varied over 16 hours, and compares that with the change in ambient temperature of our laboratory. It is clear that after the oscillator has been turned on and comes into equilibrium, the frequency is strongly correlated to the ambient temperature. These measurements are consistent with a temperature coefficient of 1.8 kHz/K. The dominant source of this effect has been traced to the existence of a substantial quadrature component in the temperature controller lock-in error voltage. A factor of 10 improvement in oscillator frequency stability is quite achievable with the rectification of this effect.

V. Conclusion

In a recently developed room temperature TE stabilized sapphire resonator-oscillator, we have measured a phase noise of -124 dBc/Hz at 1 kHz offset with a f^{-3} dependence. This noise was limited by the mixer noise floor in the phase detection circuitry. The Allan frequency deviation was also measured to be 10^{-11} at 0.1 seconds with a $\tau^{0.7}$ dependence limited by ambient temperature fluctuations.

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