Ultra-Low-Noise Microwave Oscillator with Advanced Phase Noise Suppression System

E. N. Ivanov, M. E. Tobar, and R. A. Woode

Abstract— **An advanced phase noise reduction technique has been developed to improve the short-term frequency stability of microwave oscillators. The technique is based upon an ultra-sensitive microwave frequency discriminator with effective noise temperature close to its physical temperature. The phase noise spectral density of a 9 GHz microwave loop oscillator incorporating such a discriminator has been measured as −120 dBc/Hz and −150 dBc/Hz at offset frequencies of 100 Hz and 1 kHz, respectively. This performance is at least 25 dB better than current state of the art. The developed phase noise reduction technique is quite general and can have valuable implications for the design of various low phase noise microwave oscillators.**

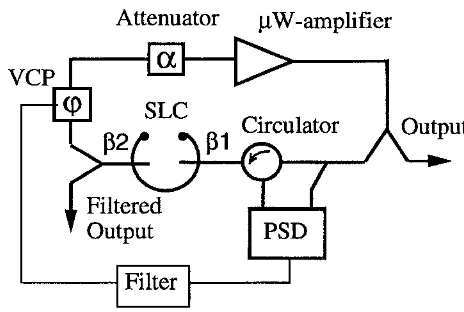

Fig. 1. Loop oscillator with phase noise reduction system.

I. Introduction

ROOM temperature high-Q sapphire loaded cavities (SLC) excited in electromagnetic modes of "whispering gallery" have allowed the design of the very low-noise microwave oscillators with the phase noise of order −125 dBc/Hz at 1 kHz offset from the carrier [1]. This performance is achieved by using a phase noise reduction technique where the resonator is used both as a bandpass filter in the loop oscillator and a dispersive element of a frequency discriminator (FD) [2], [3]. The FD acts as a frequency sensor of a control system which locks the oscillator to the center of the microwave cavity resonance.

Developing ideas of phase noise suppression discussed in [4] and [5], we have designed an advanced FD with extremely low effective noise temperature. The phase noise of a 9 GHz loop oscillator incorporating the advanced FD is equal to −150 dBc/Hz at 1 kHz offset from the carrier.

II. Oscillator Phase Noise Reduction Technique

The general configuration of the microwave loop oscillator with a phase noise reduction system is shown in Fig. 1. The FD comprises a microwave cavity and a phase detector based on the double balance mixer (DBM). The phase noise suppression is achieved by applying the filtered signal from the output of the FD to the voltage controlled phase shifter which represents an actuator of the frequency control system.

Spectral density of the oscillator phase noise at offset frequencies within the bandwidth of the high gain frequency servo is given by

$$S_\varphi^{osc}(F) = \frac{S_f^{res}(F)}{F^2} + S_\varphi^{n/f}(F) \tag{1}$$

where $S_f^{res}(F)$ is the spectral density of the SLC resonant frequency fluctuations and $S_\varphi^{n/f}(F)$ is the phase noise floor of the FD.

The first term in (1) characterizes the effect of environmental factors such as vibration on the SLC resonant frequency. It also includes the cavity's $1/F$ frequency noise. The second term in (1) is due to the noise sources which do not directly affect the SLC resonant frequency f_{res} but introduce uncertainty in the process of its measurement. In particular, the finite noise temperature of the FD $T_{\rm FD}$ imposes the following limit on the FD phase noise floor:

$$S_{\varphi 1}^{n/f}(F) = \frac{k_B T_{\rm FD}}{P_{inc}} \frac{(1+\beta)^4}{4\beta^2}\left\{1 + \left(\frac{\Delta f_{0.5}}{F}\right)^2\right\}. \tag{2}$$

Here P_{inc} is the power of microwave signal incident on the SLC, k_B is the Boltzman constant, $\Delta f_{0.5} = (f_{res}/2Q_o)(1+\beta_1+\beta_2)$, $\beta = \beta_1/(1+\beta_2)$, where β_1 and β_2 are the SLC partial coupling coefficients, and Q_o is the SLC unloaded Q-factor.

The effective noise temperature of the conventional FD, $T_{\rm FD}$, is given by

$$T_{\rm FD} = T_o + T_{\rm DBM} \tag{3}$$

where T_o is an ambient temperature and $T_{\rm DBM}$ is a DBM effective noise temperature. The latter is a function of offset frequency F and power at the DBM signal port $P_{\rm RF}$. For a typical microwave mixer WJM14A the effective noise temperature $T_{\rm DBM} \approx 8 * 10^4$ K at $P_{\rm RF} \sim 0.1$ mW and $F = 1$ kHz.

Introducing a microwave amplifier with high gain $G_{\rm AMP} \gg 1$ and low effective noise temperature $T_{\rm AMP} \ll T_{\rm DBM}$ into the

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FD allows the $T_{\rm FD}$ to be effectively reduced from the level determined by the DBM noise (3) to much lower limit given by

$$T_{\rm FD} = T_o + T_{\rm AMP} + \frac{T_{\rm DBM}}{G_{\rm AMP}} \approx T_o + T_{\rm AMP} \qquad (4)$$

which is imposed by the Nyquist noise in transmission lines and the effective noise temperature of the microwave amplifier. The minimal effective noise temperature of order $T_{\rm FD} \sim 360$ K has been measured for an advanced FD incorporating the low-noise microwave amplifier operating in the small signal regime.

The experimentally observed phase noise floor of the advanced FD follows the $1/F^2$ power law

$$S_{\varphi 1}^{n/f}(F) \sim -92 - 20\,\log_{10}(F), \qquad \frac{\rm dBc}{\rm Hz} \qquad (5)$$

within the frequency range from 30 Hz to 20 kHz. The above result is obtained for the SLC with $Q_o \approx 185000$, $\beta_1 \approx 0.75$, $\beta_2 \approx 0.15$ at the level of incident power $P_{inc} = 50$ mW. This implies that an oscillator phase noise of order $S_\varphi^{osc}(1\ \text{kHz}) \sim -152$ dBc/Hz can be potentially achieved, provided that the FD finite noise temperature is a major cause of frequency fluctuations.

III. Oscillator Phase Noise Performance

Phase noise performance of the 9-GHz loop oscillator with an advanced FD was studied by using a frequency discriminator method [6]. For this purpose a second advanced FD with similar sensitivity was built. The excellent temperature stability of both SLC's available from Poseidon Scientific Instruments enabled tuning of the readout system to be easily maintained during the whole period of the noise measurements.

Results of the oscillator phase noise measurements are shown in Fig. 2. Curve 1 shows the phase noise of the free-running oscillator. Curves 2–4 correspond to the frequency stabilized oscillator at open-loop gain $G_{op} = 38$ dB, 48 dB, and 58 dB, respectively. The power incident on the SLC is equal to 50 mW. Bright lines at the noise spectra at the frequencies of mains harmonics can be minimized by improving the electromagnetic shielding and getting rid of spurious ground loops. No traces of the phase noise degradation caused by the vibration sensitivity of oscillator-discriminator system are visible in Fig. 2.

At high loop gain ($G_{op} > 40$ dB) a single side band (SSB) phase noise of the oscillator varies as

$$L_\varphi^{osc}(F) \approx -60 - 30\,\log_{10}(F), \qquad \frac{\rm dBc}{\rm Hz} \qquad (6)$$

in the frequency range from 10 Hz to 20 kHz. This corresponds to $L_\varphi^{osc}(1\,\text{kHz}) \approx -150$ dBc/Hz which is 50 dB better than free running oscillator and represents at least 25 dB improvement with respect to the currently achieved level.

Computer simulations reveal some mechanisms affecting the phase noise floor of the frequency locked oscillator. The finite noise temperature of the FD is a major factor limiting the oscillator phase noise performance at offset frequencies from 200 Hz to 5 kHz.

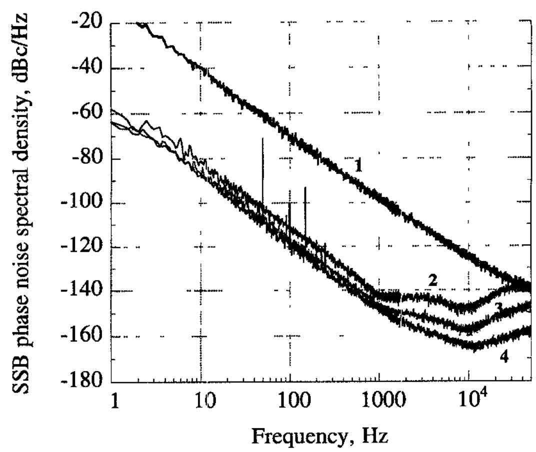

Fig. 2. Oscillator phase noise spectral density: 1) free-running oscillator, 2) frequency stabilized oscillator with dc loop gain 38 dB, 3) 48 dB, and 4) 58 dB. The oscillator operating frequency is 9 GHz, and the power incident on the SLC is 50 mW.

Another mechanism degrading the oscillator phase noise is associated with phase fluctuations in nonreciprocal ferrite components of the FD. We have recently identified this mechanism by directly measuring the phase noise in microwave circulators [7]. The experimentally obtained noise model of the typical X-band circulator is given by

$$S_\varphi^{CRL}(F) \approx -147 - 12\,\log_{10}(F), \qquad \frac{\rm dBc}{\rm Hz}. \qquad (7)$$

The circulator phase noise (7) results in $1/F^{3.2}$ component in the spectrum of the oscillator phase noise

$$S_{\varphi 2}^{n/f}(F) = S_\varphi^{CRL}(F)\left\{\frac{1-\beta^2}{2\beta}\,(1+\beta_2)\,\frac{f_{res}}{2Q_oF}\right\}^2. \qquad (8)$$

This component becomes dominant at offset frequencies below 200 Hz. At given value of the SLC Q-factor the reduction of the oscillator phase noise floor (8) can be achieved by setting the SLC coupling close to critical ($\beta \to 1$).

At high offset frequencies (above 10 kHz) the degradation of the oscillator phase noise is entirely due to the insufficient gain of the frequency servo. The further improvements in the phase noise performance at these frequencies are limited, however, by possible instability of the frequency control system.

IV. Conclusion

We have demonstrated that the new phase noise reduction technique enables drastic improvements in the oscillators phase noise performance. Applying this technique we have designed 9 GHz oscillator with phase noise -150 dBc/Hz at 1 kHz offset frequency. This is probably the first time when an oscillator's phase noise was reduced below the level of its amplitude noise. Assuming that the oscillator phase noise is primarily limited by the FD finite noise temperature, the phase noise spectral density as low as $S_\varphi^{osc}(1\ \text{kHz}) \sim -165$ dBc/Hz can be expected in future oscillators operating at high power: $P_{inc} = 500$ mW.

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