An MMIC Local Oscillator for 16-QAM Digital Microwave Radio Systems

Hideo Suwaki, Tadao Nakagawa, *Member, IEEE*, and Takashi Ohira, *Member, IEEE*

***Abstract*—The first MMIC local oscillator for 16-QAM digital microwave systems is presented. The key advance is achieving the very low phase noise required by such systems. Low phase noise is realized with a low phase noise VCO (voltage-controlled oscillator) that is installed into a new PLL (phase-locked loop). Although the developed local oscillator is 90% smaller than the existing Dielectric Resonator-based local oscillators, it achieves comparable receiver performance.**

I. Introduction

OSCILLATOR phase noise is a major hurdle to designing new receiver systems. As digital microwave systems transfer information using signal phase, oscillator phase noise degrades the BER (bit error rate). The latest oscillators use dielectric resonators to achieve sufficiently low phase noise. Unfortunately, such oscillators (DRO) increase the equipment's cost and size. DRO's are not planar, unlike most other components, so it is very difficult to reduce equipment size. Our goal was a small planar oscillator suitable for 16-QAM systems.

DRO's inherently have very low phase noise, so they can be applied without determining their actual levels of phase noise. In fact, DRO's can be considered as overkill in that their phase noise performance far exceeds system requirements. If the phase noise of an oscillator could be evaluated precisely in the design stage, it would be relatively easy and cheap to construct new types of oscillators having the necessary phase noise. Several methods to analyze oscillator phase noise have been reported [1]–[6]. However, as all method were intended for specific oscillators, it is near impossible to apply any one of them to other oscillators. We have developed a general evaluation method suitable for any oscillator. This method allows us to precisely evaluate phase noise.

To down-size communication sets, several kinds of MMIC chips and multichip modules have been proposed, including local oscillator MMIC's [7]–[11]. Despite the low Q factor of MMIC's, high frequency stability and low phase noise have been successfully obtained using phase locking [7], [10]. However, practical systems demand lower phase noise characteristics than offered by conventional PLO's (phase-locked oscillators). To overcome this problem, we proposed a new PLL.

An MMIC local oscillator for 16-QAM digital microwave systems is developed for the first time based on the new technology. The local oscillator is 94% smaller than the existing local oscillators based on DRO's. A receiver is constructed around the new oscillator and found to have performance comparable to those of existing sets. This paper describes the key technologies and the performance of an MMIC local oscillator for 16-QAM digital microwave radio systems.

Manuscript received January 17, 1994; revised November 10, 1994.

The authors are with the NTT Radio Communication Systems Laboratories, Yokosuka, Japan.

IEEE Log Number 9410707.

II. PLO Phase Noise Analysis

The block diagram of a typical MMIC PLO with additive noise sources is shown in Fig. 1. The PLO consists of a reference crystal oscillator (REF), a frequency divider (DIV), a phase/frequency comparator (PFC), a loop filter (FIL), and a voltage-controlled oscillator (VCO). The output phase noise spectral density is theoretically given as follows [12]:

$$S_{\phi_o,n}(f) = \left\{ S_{\phi_{\mathrm{REF},n}}(f) + S_{\phi_{\mathrm{DIV},n}}(f) + \frac{S_{V_{\mathrm{PFC},n}}(f) + S_{V_{\mathrm{FIL},n}}(f)}{K_d^2} \right\} N^2 |H(j2\pi f)|^2 + S_{\phi_{\mathrm{VCO},n}}(f) |1 - H(j2\pi f)|^2 \quad (1)$$

where K_d is the phase detector sensitivity constant, N is a division ratio, $S_\phi, \cdots, n(f)$ is the noise power spectral density, and $H(j2\pi f)$ is the transfer function of loop filter. In the loop filter passband ($|H(j2\pi f)| \approx 1$), all the loop elements noise except the VCO noise contribute to the PLO noise, and outside the loop filter passband ($|H(j2\pi f)| \approx 0$), the PLO output noise is equal to the VCO noise.

The contributions of the noise power spectral density to the MMIC PLO output in the passband have been estimated experimentally [13]. The results, shown in Fig. 2, indicate that the PFC noise is the dominant PLO noise.

III. New Phase Locked Loop

The new loop configuration is shown in Fig. 3. From (1), it is found that the PFC noise contribution can be suppressed by increasing K_d. An exclusive-OR (EXOR) is used here since its K_d is twice that of the PFC. However, the pull-in range of the single EXOR loop is narrow. To overcome this problem, the frequency comparison signal of the PFC is added to the phase detection signal of the EXOR. The cutoff frequency of the PFC loop filter is very low (several hertz) so that only the frequency comparison signal is obtained and the PFC noise is eliminated. Therefore, a PLO with low phase noise and a wide pull-in range can be achieved.

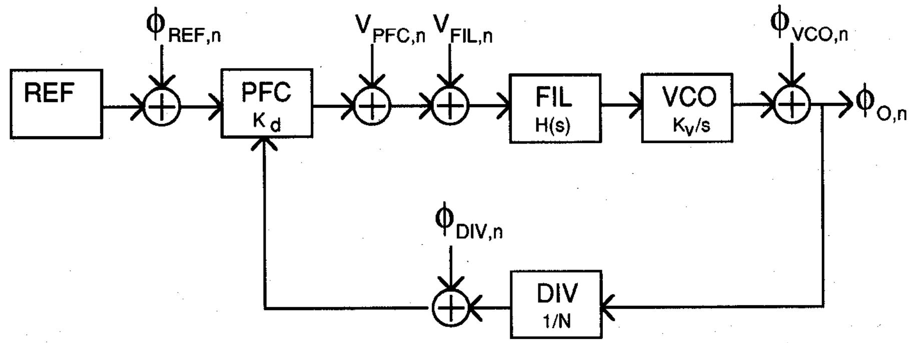


Fig. 1. Diagram of PLO with additive noise sources.

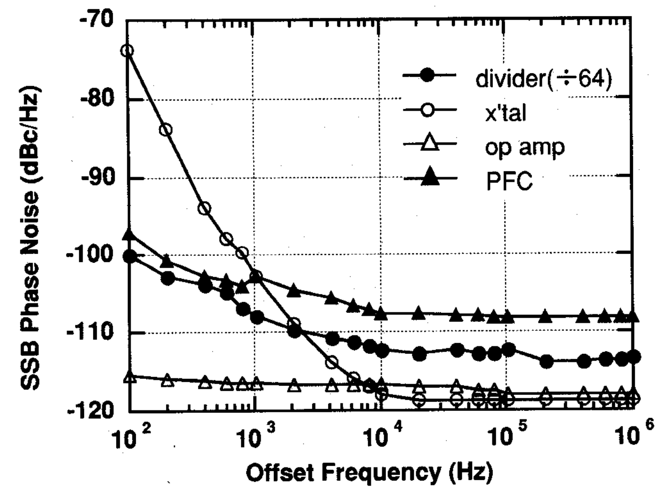


Fig. 2. Estimated noise contributions with respect to 5-GHz PLO output.

IV. Required Performance of VCO

The performance required for the target system is a phase noise of -50 dBc or better as integrated from 3.8 kHz–10 MHz offset from the carrier. The phase noise of the VCO is expected to be less than -125 dBc/Hz at 1-MHz offset frequency according to estimations based on (1). In general, phase noise is inversely proportional to the variation in frequency range. Although the variation in frequency range must be small to reduce the phase noise, the frequency range should cover the frequency error generated by implementation and the change caused by environmental temperature. We determined that the required variation in range is about 100 MHz.

V. Low Phase Noise VCO

The negative resistance type oscillator circuit is shown in Fig. 4. The oscillation conditions are

$$R(\omega_0) - \overline{R}(\omega_0) < 0 \quad \text{and} \quad X(\omega_0) + \overline{X}(\omega_0) = 0 \tag{2}$$

where

$$\begin{aligned} Z &= Z_D + Z_R = Z_{D1} + Z_{D2} + Z_R = R_1 + R_2 - \overline{R} \\ &\quad + j(X_1 + X_2 + \overline{X}) \equiv R - \overline{R} + j(X + \overline{X}). \end{aligned}$$

$Z_{D1} = -\overline{R} + j\overline{X}$ is the impedance of the negative resistance generator. $Z_{D2} = R_2 + jX_2$ and $Z_R = R_1 + jX_1$ represent

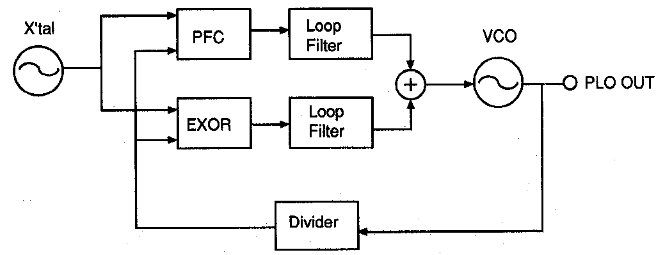


Fig. 3. New configuration for PLO phase noise reduction.

the passive parts of the negative resistance generator and the resonator circuit, respectively. The phase noise of the oscillator is caused by fluctuation of the oscillation current driven by the noise close to the oscillation frequency. This noise consists of the noise that inherently exists close to the oscillation frequency and that upconverted from low frequencies by the nonlinearity of the active devices. Oscillator phase noise can be described as follows [14]:

$$L(\omega_m) = \frac{\left(\frac{|e(\omega_0+\omega_m)|^2}{R(\omega_0+\omega_m)} + \frac{|e(\omega_m)|^2}{R(\omega)m)}G\right)}{2P} \cdot \left(\frac{\omega_0}{2Q\omega_m}\right)^2 (1+\alpha) \tag{3}$$

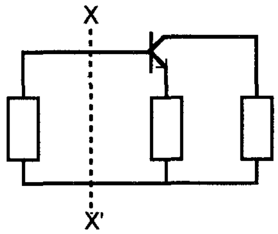
where

$$Q = \frac{1}{2}(t^2+u^2)^{1/2}, \quad \alpha = \frac{(su+rt)^2}{(ru-st)^2}, \quad P = \frac{1}{2}A^2R$$

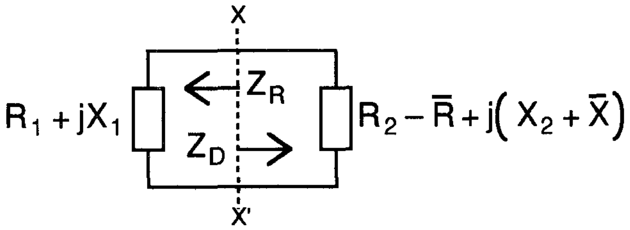
$$t = \frac{\omega_0}{R}\frac{\partial X}{\partial \omega}, \quad u = \frac{\omega_0}{R}\frac{\partial R}{\partial \omega}, \quad r = \frac{A}{R}\frac{\partial X}{\partial A}, \quad s = \frac{A}{R}\frac{\partial R}{\partial A}$$

e is noise voltage
A is magnitude of oscillation current
G is upconversion gain from ω_m to $\omega_0 + \omega_m$.

The combination of using a low-noise device and raising the Q factor is effective for creating a low-phase-noise oscillator. As Si BJT's [15] have lower noise than GaAs MESFET's [16] at low frequencies, a Si BJT was used to construct the negative-resistance generator. However, Si substrates are not suitable as transmission lines because of their high insertion loss. Accordingly, we formed a microstrip line resonator on an alumina substrate and externally connected it to a Si MMIC chip and a hyperabrupt GaAs varactor diode. Fig. 5



(a)



(b)

Fig. 4. (a) Negative resistance type oscillator circuit. (b) Equivalent circuit.

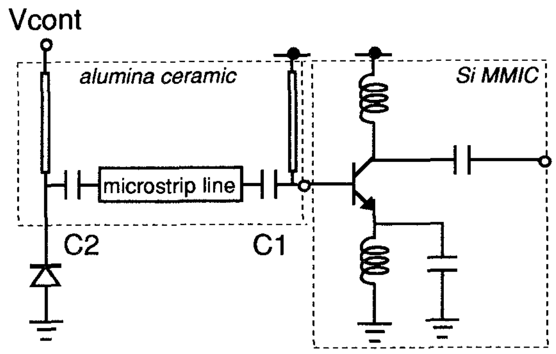
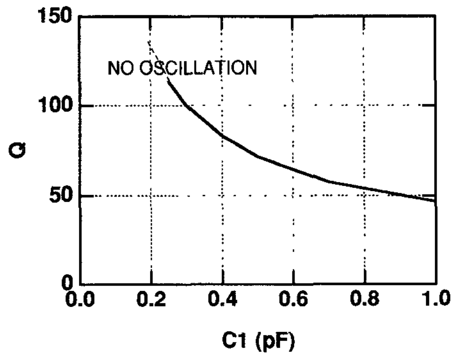


Fig. 5. Developed VCO configuration.

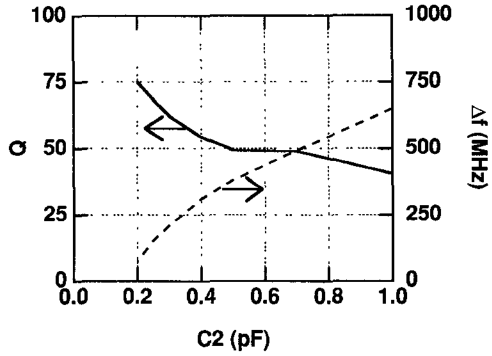
shows the VCO configuration. As a direct connection would reduce the Q factor of the oscillator, the resonator was connected to the Si MMIC and the varactor diode through a small capacitor. Adequate capacitors were used to satisfy the required frequency variation range and phase noise. The relation between Q and the capacitance of $C1$ is shown in Fig. 6(a) without capacitor $C2$. The condition of (2) can only be realized if $C1$ exceeds 0.25 pF. We set $C1$ at 0.3 pF. The relation between Q, variable frequency range, and the capacitance of $C2$ is shown in Fig. 6(b) with $C1 = 0.3$ pF. Capacitor $C2$ is set at 0.25 pF to achieve the required phase-noise performance and frequency variation range. The phase noise calculated from (3) with selected $C1$ and $C2$ values are shown in Fig. 7 for three values of varactor diode control voltage, V_{cont}. The results show that the proposed VCO has a phase noise of less than -125 dBc/Hz at 1-MHz offset frequency.

VI. VCO Performance

Fig. 8 shows the oscillation frequency and output power versus V_{cont}. The VCO has a frequency variation range of about 90 MHz. The output power characteristics are flat. The difference between measured frequency and calculated performance as determined from (2) is less than 0.5%.



(a)



(b)

Fig. 6. The relation between Q, variable frequency range, and the value of capacitors (a) $C1$ and (b) $C2$.

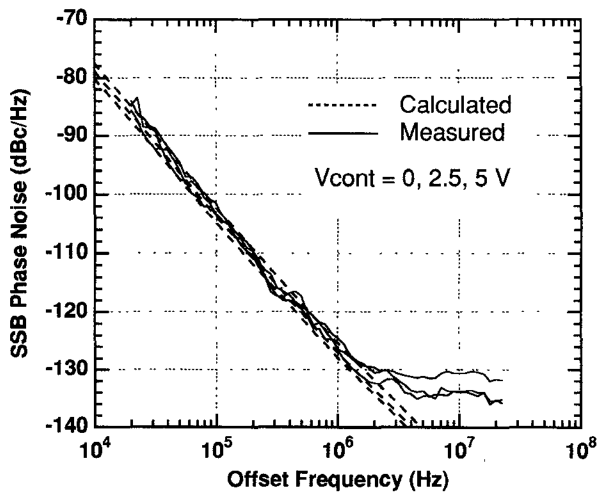


Fig. 7. Phase-noise characteristics of the VCO.

VII. PLO Performance

A photograph of the local-oscillator module prototype is shown in Fig. 9. The VCO, amplifier, divider, and phase detector form one package. A crystal oscillator and loop filters are connected to the module. A complete PLO is shown in Fig. 10. The volume of the developed PLO is 90% smaller than those now in use. Fig. 11 shows the phase-noise characteristics of the phase-locked oscillator. The dashed line represents characteristics predicted by (1). The integration phase noise from 3.8 kHz to 10 MHz was -50.9 dBc, which satisfies the phase noise requirement. Fig. 12 plots the temperature characteristics from -10–$60°$C. In all range, the PLO requirements are satisfied.

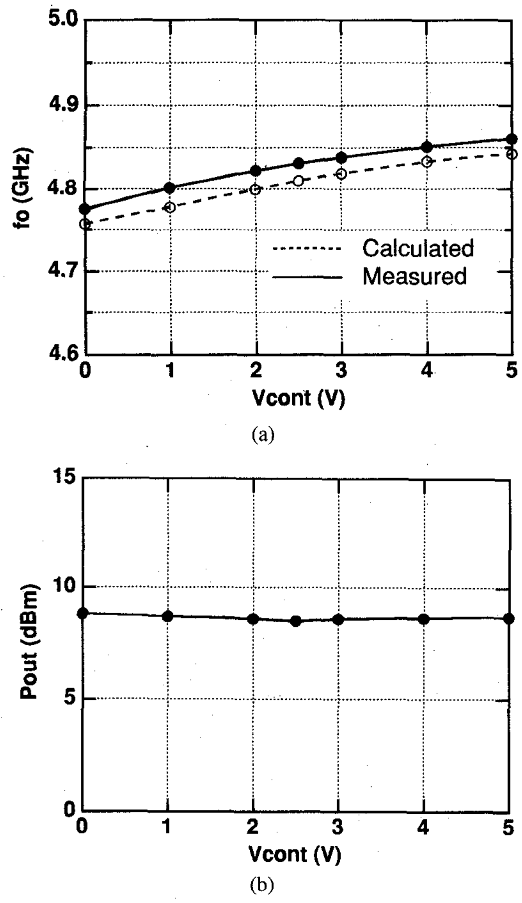


Fig. 8. Developed VCO performance.

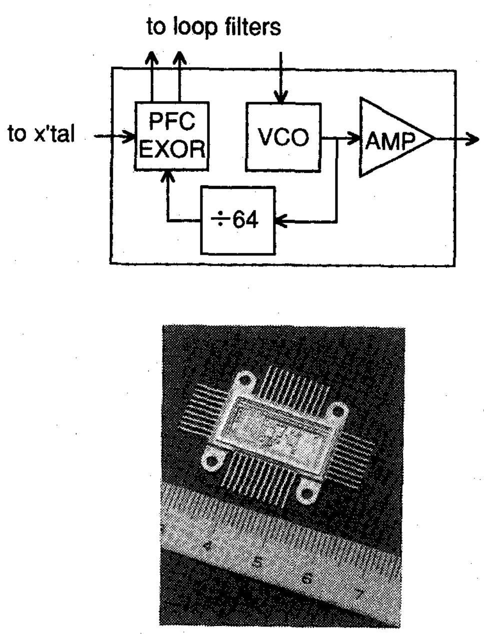


Fig. 9. A photograph of the developed local oscillator module.

VIII. Bit Error Characteristics

The BER characteristics of the developed local oscillator were examined. Measurement configuration is shown in Fig. 13. An existing DRO local oscillator in a commercial 16-

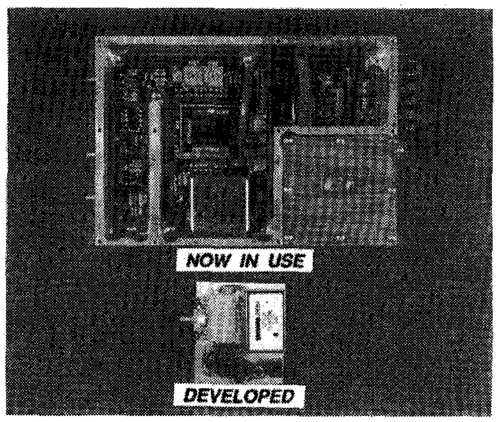


Fig. 10. A photograph of the developed PLO.

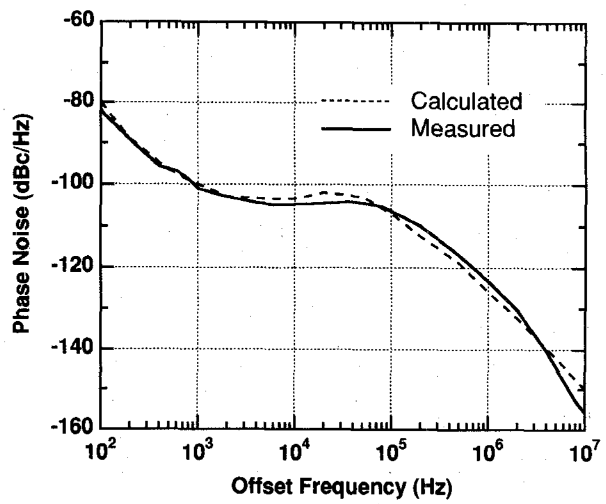


Fig. 11. The phase noise characteristics of the developed PLO.

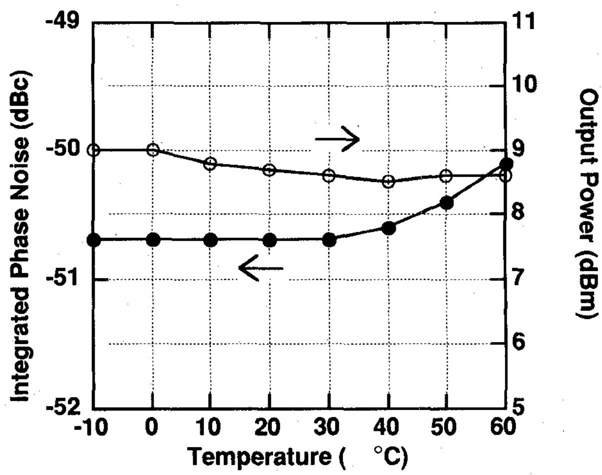


Fig. 12. Temperature characteristics of the developed PLO.

QAM set was replaced with the new oscillator. Fig. 14 shows the measured BER characteristics of the receiver as well as that of the modem only. Measured data (•) show the BER when the modem (MOD) was directly connected to point (*) shown in Fig. 13. The CNR degradation of overall performance was less than 0.3 dB at a BER of 10^6. This is comparable to the effect recorded with DRO local oscillators. This result confirms that

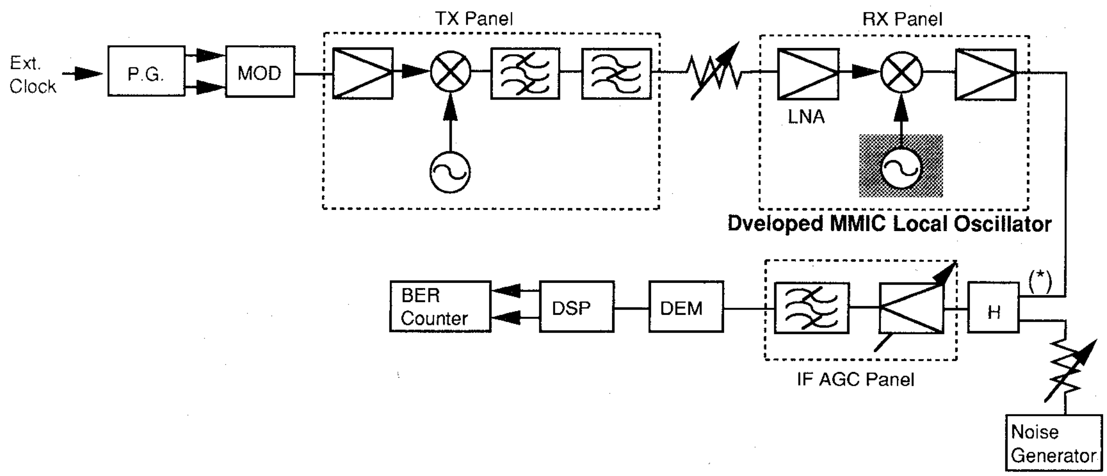


Fig. 13. The configuration for measuring BER characteristics.

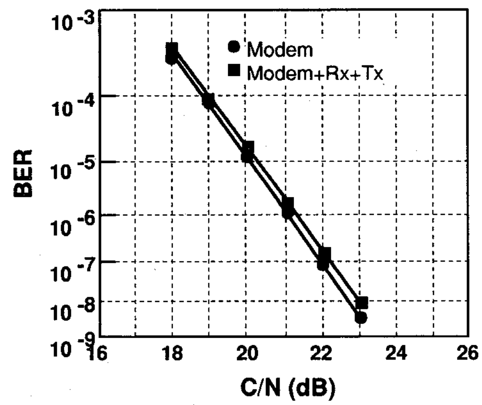


Fig. 14. The bit error rate characteristics of the receiver with the developed MMIC local oscillator.

the developed local oscillator is applicable to 16-QAM digital microwave radio systems.

IX. Conclusion

The first MMIC local oscillator for 16-QAM digital microwave radio systems has been developed. Two key technologies have been proposed: a new phase-locked loop and a low phase noise VCO. Very low noise characteristics (less than -100 dBc/Hz at 1-kHz offset from the carrier) were achieved. The phase noise value of the MMIC local oscillator is 10 dB lower in the passband of loop filter and 20 dB lower in the stopband than conventional phase-locked oscillators using GaAs MMIC VCO's. This low phase noise performance allows the developed MMIC local oscillator to be used in 16-QAM systems. The MMIC oscillator will significantly reduce equipment cost and size.

References

[1] K. Kurokawa, "Noise in synchronized oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, no. 4, pp. 234–240, Apr. 1968.

[2] ——, *Introduction to the Theory of Microwave Circuits.* New York: Academic, 1969, ch. 9.

[3] ——,"Some basic characteristics of broadband negative resistance oscillator circuits," *Bell Syst. Tech. J.*, pp. 1937–1955, July–Aug. 1969.

[4] B. T. Debny and J. S. Joshi, "A theory of noise in GaAs FET microwave oscillators and its experimental verification," *IEEE Trans. Electron Dev.*, vol. ED-30, no. 7, pp. 769–775, July 1983.

[5] H. Siweris and B. Schiek, "Analysis of noise upconversion in microwave FET oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, no. 3, pp. 233–242, Mar. 1985.

[6] O. A. Abo Elnor, A. Jacob, and K. Schünemann, "Figure of merit for characterizing FET oscillators," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1990, pp. 1265–1268.

[7] T. Ohira, H. Kato, K. Araki, and F. Ishitsuka, "A compact full MMIC module for Ku-band phase-locked oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. 37, no. 4, pp. 723–728, Apr. 1989.

[8] J. Archer, B. M. Smith, G. R. Weaver, H. Wong, and J. Y. Yoneyama, "Development and evaluation of a GaAs MMIC phase-locked loop chip set for space applications," *IEEE Trans. Microwave Theory Tech.*, vol. 37, no. 4, pp. 790–792, Apr. 1989.

[9] W, Yau, M. I. Mendolia, C. P. Wen, and J. C. Chen, "An X-band low cost GaAs monolithic transceiver," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1990, pp. 827–830.

[10] T. Ohira, M. Muraguchi, M. Hirota, K. Osafune, and M. Ino, "Dual chip GaAs monolithic integration Ku-band phase-locked-loop microwave synthesizer," *IEEE Trans. Microwave Theory Tech.*, vol. 38, no. 9, pp. 1204–1209, Sept. 1990.

[11] T. Kaneko, T. Miya, and S. Yoshida, "A Ku band converter IC," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1992, pp. 451–454.

[12] V. F. Kroupa, "Noise properties of PLL systems," *IEEE Trans. Commun.*, vol. COM-30, no. 10, pp. 2244–2252, Oct. 1982.

[13] T. Nakagawa, H. Suwaki, and T. Ohira, "Low-noise MMIC phase-locked oscillators using an EXOR and a PFC," *IEICE Trans. Electron.*, vol. E76-C, no. 6, pp. 950–954, June 1993.

[14] H. Suwaki and T. Hirota, "Phase noise evaluation of microwave oscillator phase noise," to be published in *IEEE Trans. Microwave Theory Tech.*

[15] S. Kondo, Y. Amemiya, K. Sakuma, and T, Sakai, "A 20 ps/G Si bipolar IC using advanced SST with collector ion implantation," in *Extended Abstr. 19th SSDM*, 1987, pp. 331–334.

[16] T. Enoki, K. Yamasaki, and K. Osafune, "0.3-μm advanced SAINT FET's having asymmetric n-layers for ultra-high-frequency GaAs MMIC's," *IEEE Trans. Electron Dev.*, vol. 35, no. 1, pp. 18–24, Jan. 1988.

Hideo Suwaki was born in Okayama, Japan, on September 12, 1961. He received the B.E. degree from Kyushu Institute of Technology in 1985 and the M.E. degree in electronics engineering from Kyushu University, Fukuoka, Japan, in 1987.

In 1987, he joined NTT Radio Communication Systems Laboratories, Yokosuka, Japan. He was engaged in research and development on MMIC filters and oscillators.

Tadao Nakagawa (M'92) was born in Kobe, Japan, on July 21, 1963. He received the B.E. and M.E. degrees in material physics from Osaka University, Osaka, Japan, in 1986 and 1988, respectively.

In 1988, he joined NTT Radio Communication Systems Laboratories, Yokosuka, Japan, and since then he has been involved in research on GaAs MMIC circuits. He is currently a research engineer of NTT Wireless Systems Laboratories, Yokosuka, Japan, where he is engaged in the development of microwave synthesizers.

Mr. Nakagawa is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.

Takashi Ohira (S'79–M'83) was born in Osaka, Japan, on April 10, 1955. He received the B.E. and D.E. degrees in communication engineering from Osaka University, Osaka, Japan, in 1978 and 1983, respectively.

In 1983, he joined NTT Electrical Communication Laboratories, Yokosuka, Japan, where he was engaged in research on monolithic integration of microwave semiconductor devices and circuits. From 1987 to 1992, he was a senior research engineer at NTT Radio Communication Systems Laboratories, Yokosuka, Japan, where he was responsible for the development of GaAs MMIC transponder modules for Japanese domestic multibeam communication satellites. He is currently a senior manager of NTT Wireless Systems Laboratories, Yokosuka, Japan.

Dr. Ohira was awarded the 1986 Shinohara Prize by the Institute of Electronics and Communication Engineers of Japan. He is a member of the Institute of Electronics, Information and Communication Engineers (IEICE) of Japan.