tain

$$U_m - U_e = \frac{\mu_0}{4}\iint_S [\mu\phi^2 - \kappa\bar{\beta}^2\psi^2]\,dS - \frac{\mu_0}{4}\iint_S \frac{1}{k^2}[\mu|\nabla_t\phi|^2 - \kappa\bar{\beta}^2|\nabla_t\psi|^2]\,dS = 0. \quad (14)$$

In expression (14), the term coupling ϕ and ψ together on the boundary disappears but the expression is not variational. This is because the integrand is not necessarily positive definite.

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Q-Dependence of Gunn Oscillator FM Noise

H. HERBST AND A. ATAMAN

***Abstract*—Measurements of FM noise and the external quality factor Q_{ex} of X-band Gunn oscillators are reported which show that both upconverted and intrinsic FM noise vary inversely as Q_{ex}, if bias voltage, RF power, and frequency are kept constant.**

The FM noise spectrum of a Gunn oscillator consists of two parts, the intrinsic noise and the upconverted noise. In this letter it is shown experimentally that both parts depend inversely on the quality factor Q_{ex} of the resonant circuit. This result is in agreement with theory.

At low modulation frequencies f_m the FM noise of a Gunn oscillator is ruled by upconversion of low-frequency fluctuations of the device impedance. The mean-square noise current usually decreases as $1/f_m$ resulting in a $1/f_m^{1/2}$ behavior of the mean frequency deviation Δf_{rms}. Towards higher frequencies off the carrier (above 100 kHz) white intrinsic noise due to amplification of thermal noise predominates.

Recently, successful efforts have been made to reduce FM noise by a stabilizing high-Q cavity [1], whereas AM noise remained essentially unchanged within the bandwidth of the cavity [2]. For this reason and because AM noise power is much less than FM noise power for Gunn oscillators near the carrier, only FM noise is treated in this work. For practical applications, it is of considerable interest to know the Q_{ex} dependence of both parts of FM noise. Several authors have investigated this problem. Cathelin *et al.* [3] measured $\Delta f_{rms}\sqrt{Q_{ex}}$ to be fairly independent of Q_{ex} for modulation frequencies between 2 and 100 kHz. Sweet and MacKenzie [4] found Δf_{rms} to depend on the voltage pushing only and not on Q_{ex} for upconverted noise and to vary as $(Q_{ex}\cdot\sqrt{P_0})^{-1}$ for intrinsic noise, where P_0 is the RF power of the oscillator. The contradiction in these results is mainly because of the fact that the investigations did not take into account the dependence of the noise on the device impedance and its derivatives with respect to the modulating parameters or the RF voltage amplitude.

The basic equation for both upconverted and intrinsic noise is the condition of oscillation [5]:

$$A(t)[Y_D(M(t)) + Y_L(f)] + e_c(t) + je_s(t) = 0. \quad (1)$$

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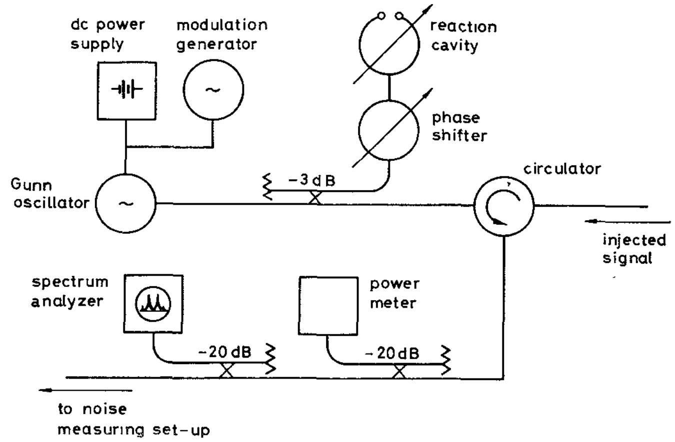

Fig. 1. Schematical plot of the Q-measuring setup.

$Y_D = G_D + jB_D$ and $Y_L = G_L + jB_L$ are the admittances of the device and the load, respectively. $A(t)$, $M(t)$, $e_c(t)$, and $e_s(t)$ are slowly varying functions of time. $A(t)$ is the RF voltage amplitude, $M(t)$ some modulating parameter as, e.g., carrier density, bias voltage, or temperature, giving rise to upconverted noise, and $e_c(t)$ and $e_s(t)$ represent the primary noise source near the carrier frequency f_0. The device admittance may only depend on M and not on the frequency f, which is an appropriate description for a Gunn element. Small fluctuations of the modulating parameter M result in fluctuations of the diode admittance Y_D which have to be taken into account in (1) as

$$\Delta Y_D(t) = \frac{\partial Y_D}{\partial M}\Delta M(t) = \frac{1}{A}(a_c(t) + ja_s(t)). \quad (2)$$

Neglecting all terms causing AM noise, both upconverted and intrinsic FM noise are described by a single expression as pointed out by Kurokawa [5]:

$$\Delta f_{rms} = \frac{f_0}{Q_{ex}}\sqrt{\frac{(e_s)_{rms}^2 + (a_s(f))_{rms}^2}{4|G_D|P_0}} \quad (3)$$

$$= \frac{f_0}{Q_{ex}}\sqrt{\frac{kT_{eq}(f)B}{P_0}} \quad (4)$$

where k is Boltzmann's constant, T_{eq} the frequency dependent equivalent noise temperature of the noise sources involved, and B is the measuring bandwidth. Equation (4) was first derived by Edson [6] for the case of pure intrinsic noise.

For upconverted noise it is obvious from (2) and (3) that Δf_{rms} varies inversely as Q_{ex} if carrier frequency f_0, output power P_0, and bias voltage V_B are kept constant. The same holds for intrinsic noise because the primary RF noise source depends on the negative conductance [7] and, consequently, on the output power P_0 of the Gunn oscillator. Therefore, the relation $\Delta f_{rms}\sqrt{P_0}\sim Q_{ex}^{-1}$, often taken as evidence for intrinsic noise, only holds for the special condition that T_{eq} is independent of P_0. This can only be the case in a small range of operation parameters.

Equation (4) does not take into account AM–FM and FM–AM conversion. This is done by considering the dependence of the device admittance on the RF amplitude A. A linearized theory [8] leads to an expression for the frequency fluctuation:

$$\Delta f(t) = \frac{f_0\left[-i_s(t) + i_c(t)\left(\frac{\partial B_D}{\partial A}\Big/\frac{\partial G_D}{\partial A}\right)\right]}{2AG_L\cdot Q_{ex}\left[1 - \left(\frac{\partial B_D}{\partial A}\Big/\frac{\partial G_D}{\partial A}\right)\left(\frac{\partial G_L}{\partial f}\Big/\frac{\partial B_L}{\partial f}\right)\right]} \quad (5)$$

where $i_s(t) = e_s(t) + a_s(t)$ and $i_c(t) = e_c(t) + a_c(t)$. AM–FM conversion is described by the second term of the numerator, whereas the second term in the brackets of the denominator represents FM–AM conversion. With $Q_{ex} = (f_0/2G_L)(\partial B_L/\partial f)$, one obtains that Δf_{rms} will always vary inversely as Q_{ex} when FM–AM conversion can be neglected.

Q_{ex} measurements were carried out using the modulation method of Ashley and Palka [9]. The measuring setup is shown in Fig. 1. This method allows to determine the quality factor rather exactly

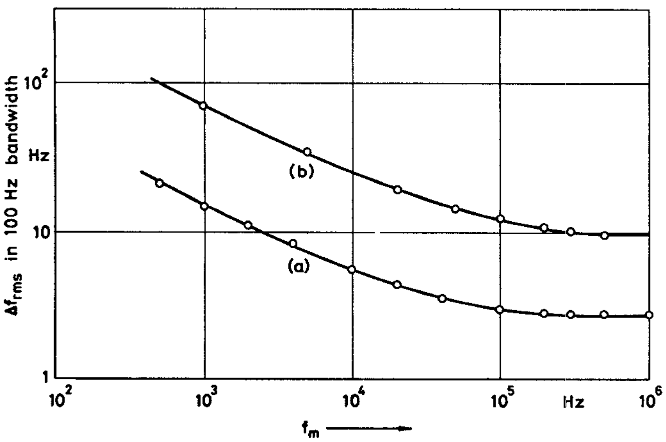

Fig. 2. Mean frequency deviation Δf_{rms} versus modulation frequency f_m; measuring bandwidth 100 Hz, bias voltage $V_B = 7$ V, and frequency $f_0 = 12$ GHz; (a) optimum power output $P_0 = 60$ mW, $Q_{ex} = 150$; (b) power output $P_0 = 14.7$ mW, $Q_{ex} = 122$.

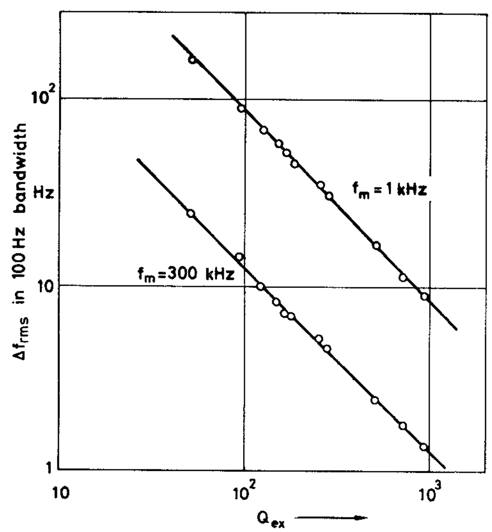

Fig. 3. Δf_{rms} in bandwidth 100 Hz versus external quality factor Q_{ex} for $f_m = 1$ kHz and $f_m = 300$ kHz.

near the carrier frequency and helps to avoid errors which can occur because of asymmetric synchronizing ranges when using the conventional method reported by Adler [10]. The quality factor was varied with an external high-Q reaction cavity coupled to the oscillator by a 10-dB or a 3-dB directional coupler (see Fig. 1). With the tunable phase shifter the angle between $Y_D(A)$ and $Y_L(f)$ on the complex plane could be varied [11], [12], which resulted in a change of Q_{ex}.

The FM noise was measured with a direct detection system employing a high-Q transmission cavity as a discriminator. The Gunn oscillator used had an optimum output power of 60 mW at 12 GHz. It was fabricated from GaAs epitaxial material grown in this laboratory. The FM noise spectrum is represented by curve (a) in Fig. 2 for modulation frequencies between 500 Hz and 1 MHz. The dependence on f_m is just as described above. In order to be able to keep V_B, P_0, and f_0 constant when varying Q_{ex}, it was advantageous to tune the oscillator to a lower power output. Curve (b) in Fig. 2 shows the FM noise obtained at this operating point.

The mean frequency deviation Δf_{rms} was measured at 1 kHz and 300 kHz off the carrier, well within the range of predominating upconverted noise and intrinsic noise, respectively. Q_{ex} was in the range between 50 and 1000. These values are much greater than the quality factor of the Gunn element itself, which is of the order of unity. Therefore, the load quality factor can be taken to characterize the oscillator behavior. This agrees with the neglection of frequency dependence of the device admittance in (1).

The results are given in Fig. 3. Both the upconverted noise and the intrinsic noise decrease as $1/Q_{ex}$ as predicted by theory. FM–AM conversion is of no importance, at least in this particular case. The Q_{ex} dependence observed could not be obtained by only changing Q_{ex} without taking care of the other parameters mentioned above. As far as intrinsic noise is concerned this means that the high-frequency noise source indeed depends on output power and device admittance. Further work is in progress to investigate this dependence.

Acknowledgment

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Temperature Stability of an MIC Gunn-Effect Oscillator

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***Abstract*—A technique to temperature stabilize a Gunn-effect CW oscillator (*C* band) in microstrip, has been developed.**

An asymmetric dielectric loading technique has been used to minimize the temperature dependence of frequency of a microstrip Gunn oscillator. This technique compensates for the temperature dependence of the dielectric constant of the microstrip and GaAs. A titanate[1] ceramic disk ($\epsilon = 150$) with a diameter of 0.25 in and 0.025 in thick provided the means of temperature stabilization. This material has good microwave properties and exhibits a strong increase in permittivity with decreasing temperature.

Reflection measurements were made on a straight-line microstrip resonator $\lambda/2$ long at 7.46 GHz. A conventional 99.5-percent pure 0.025-in-thick alumina substrate was used. The variation in resonant frequency was monitored over a temperature range of -55 to $+70$°C. The resultant slope was -0.4 MHz/°C and is shown in Fig. 1. Placement of the disk on the microstrip (Fig. 2) to achieve optimum temperature stability was determined by trial and error. The best slope obtained was -0.032 MHz/°C.

The dielectric loading technique was then used with a microstrip CW Gunn oscillator by placing the disk over the frequency-dependent tuning element. The best result obtained was -40 kHz/°C over a temperature range of -55 to $+70$°C as shown in Fig. 3. Critical coupling was characterized by a reduction of 240 MHz in the oscillator frequency. The reduced center frequency was 6.3 GHz. Similar results were achieved from 5.8 to 6.8 GHz by properly adjusting the

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