NOISE AND DISTURBANCES

Ch.2
Types of noise

Thermal noise

Origin

This type of noise originates from the thermal agitation of the free electrons in a dissipative environment (resistance), which leads to spontaneous agglomerations of carriers at the ends.

Nyquist's theorem for linear systems

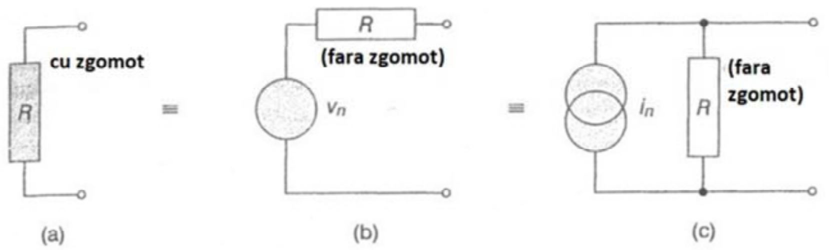

Fig.2.1

$$S(V_n) = \frac{\overline{v_n^2}}{\Delta f} = 4kTR\left[V^2/Hz\right] \qquad (2.1)$$

$$S(I_n) = \frac{\overline{i_n^2}}{\Delta f} = \frac{4kT}{R} = 4kTG\left[A^2/Hz\right] \qquad (2.2)$$

This theorem states that the spontaneous fluctuations of voltage at the terminals (or currents) of a linear resistor R, maintained in thermal equilibrium at temperature T, are independent of the conduction mechanisms, the nature of the material, the geometry or the dimensions of the resistance. These fluctuations depend only on the value of the resistance and the temperature T expressed in Kelvin degrees.

The spectral density of the open noise voltage vn (which is the average quadratic value in a unitary Δf band) is given by the relation (2.1).
The spectral density of the short-circuit noise current in (which is the average quadratic value in a unitary Δf band) is given by the relation (2.2).

Generalizations of Nyquist's theorem

- The case of arbitrary impedance

$$S\left(I_n\right) = 4kT\Re\left\{Z^{-1}\right\} = \frac{4kTR}{R^2 + X^2} \qquad (2.3)$$

- The case of several interconnected impedances

$$\overline{v_n^2} = 4kT\int_0^{+\infty} \Re\left\{Z\right\} df \qquad (2.4)$$

<u>The case of arbitrary impedance</u>
Let a dipole in thermal equilibrium, of impedance Z = R + jX. The expression (2.2) becomes (2.3).

<u>The case of several interconnected impedances</u>
If the dipole consists of several impedances, the noise current or voltage at its terminals can be calculated by looking for the real part of the impedance seen at the terminals to which the relation (2.4) is applied. This is called Nyquist's formula.

Characteristics

1.The spectral distribution of power is uniform, at least up to very high frequencies where quantum correlation is required. In practice it is considered that this limit is reached for $f_c = 0.15kT10^{34}$[Hz].

2. Instantaneous amplitudes of thermal noise have a normal (Gaussian) distribution. The average value is null and the effective value is the square root of the right member of Eq. (2.1) or (2.2)

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Shot noise

Origin

This noise has its origin in the granular nature of the electric current and in the passing of the charge carriers through a potential barrier.

Shot noise

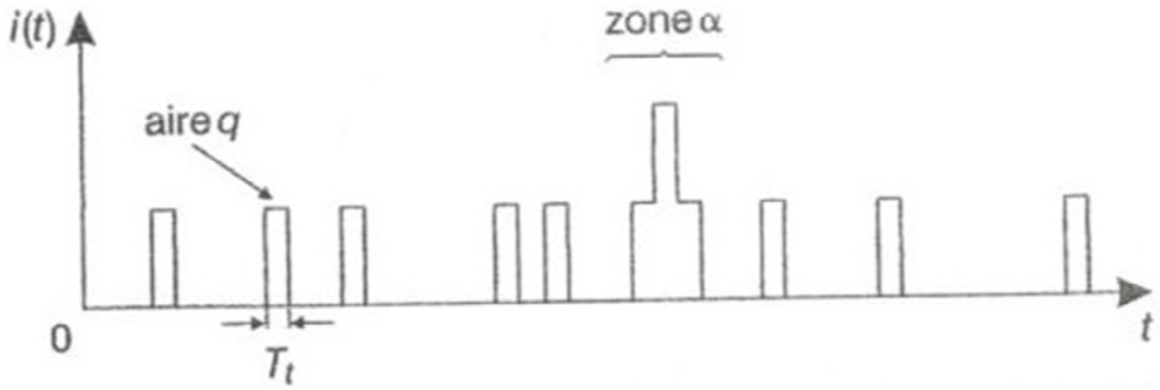

Fig.2.2

Each time a load carrier crosses a potential barrier (for example the depopulated area of a PN junction), an elementary impulse of current appears. This situation is illustrated in fig 2.2, produced by passing individual carriers. In the alpha area, we have a pack of 4 carriers of which 2 cross the barrier simultaneously. We noted with Tt the transit time (defined as the time required for the carrier to cross that region). Overlaying the elemental impulses due to a very large number of carriers, the resulting instantaneous value will be fluctuations around an average value.

Shot noise

$$i(t) = q\sum_i \delta(t - t_i) \quad (2.5)$$

$$\overline{i(t)} = I_0 = \lambda q \quad (2.6)$$

$$S(I) = 2qI_0\left[A^2/Hz\right] \quad (2.7)$$

$$\overline{i_n^2} = 2qI_0\Delta f \quad (2.8)$$

The instantaneous current can be put in the form (2.5), a sum of Dirac impulses of magnitude q.
The average value is Eq. (2.6), where λ is the average number of electrons passing the barrier in a second.
The spectral (unilateral) density of the shot noise current is Eq. (2.7) (considering only the positive frequencies). This spectrum is a white spectrum.
The average quadratic value of the fluctuating component superimposed on the average current I0 is given by Schottky's theorem, Eq. (2.8)

The case of a PN junction

$$I = I_S\left(\exp\left(\frac{qV}{kT}\right)-1\right) \quad (2.9)$$

$$\overline{i_{n,tot}^2} = \left(2qI_S\exp\left(\frac{qV}{kT}\right)+2qI_S\right)\Delta f = 2q\left(I+2I_S\right)\Delta f \quad (2.10)$$

$$g_m = \frac{dI}{dV} = \frac{qI}{kT} \quad (2.11)$$

$$\overline{i_{n,tot}^2} \simeq 2qI\Delta f = 2kTg_m\Delta f\left[A^2\right] \quad (2.12)$$

The current in a PN junction consists of the injection of minority carriers through the junction, followed by their diffusion and recombination.
The total current is expressed as Eq. (2.9), where V is the applied voltage and Is is the saturation current. This total current can be considered as the sum of two currents, Is * exp (qV / kT) and respectively –Is. Starting from the principle that the two currents fluctuate independently, we have Eq. (2.10).
The low frequency differential conductance is given by Eq. (2.11), which allows, in the case of a directly polarized junction, to give an approximate relation of Eq. (2.10) in the form of Eq. (2.12).
The expression (2.12) compared to the relation (2.2), shows that the shot noise of a PN junction, directly polarized, is equal to half of the thermal noise generated by a resistance equivalent to the differential resistance.

The case of a metal-semiconductor junction

$$S(I_{tot}) = 2q(I + 2I_S) \quad (2.13)$$

$$S(I_{tot}) = 2kTg_m \frac{(I + 2I_S)}{I + I_S} \quad (2.14)$$

In the case of this junction, we have two types of carriers:
1) The carriers that come from metal in the semiconductor and that must cross a potential barrier of height E0.
2) Carriers that come from semiconductor to metal, which meet a potential barrier q (øc-V), where øc is the contact potential. It can be shown that this current, denoted I, is proportional to exp (qV / kT).

The total current being the sum of these two currents, the spectral density of total noise current is Eq. (2.13).
Using the differential conductance gm, we obtain Eq. (2.14).

Avalanche noise

Origin
This noise is related to the avalanche multiplication of the carriers in a reverse polarized PN junction.

Avalanche noise

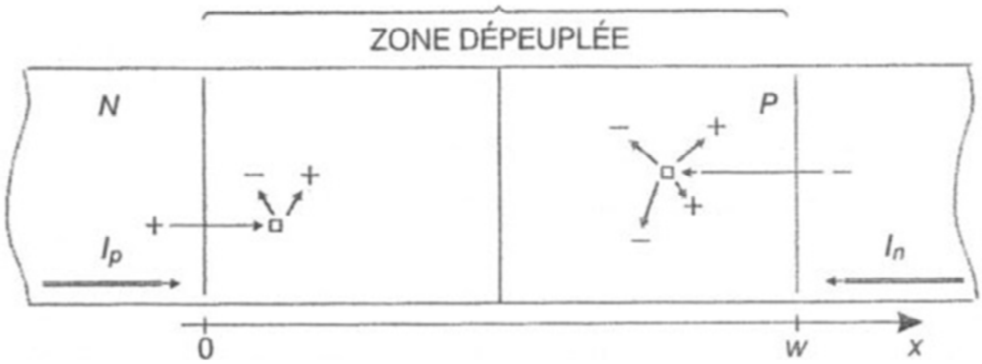

Fig.2.3

When an applied reverse voltage increases to the breakdown, the electric field becomes more and more intense. Under its influence, minority charge carriers (electrons in material P and holes in material N) are accelerated and gain enough energy to generate one or more electron-hole pairs at each collision with the nodes of the crystalline network (fig. 2.3).

Avalanche noise

$$\overline{i^2} = 2qI_0\overline{M^2}\Delta f \quad (2.15)$$

$$S(I) = 2qI_0\overline{M^2}\left[A^2/Hz\right] \quad (2.16)$$

$$I_0 = I_p(0) + I_n(w) + qA\int_0^w g(x)\,dx \quad (2.17)$$

In the case of the carriers generated by the avalanche, the noise associated with their passage is much more complex, because the multiplication factor M of the carriers is a random variable of distance (see fig. 2.3) and time. Moreover, the probability of generating by impact other carriers is not the same for electrons and holes. However, assuming that M is independent of x, the expression of the avalanche noise current is (2.15), which leads to the spectral density of current (2.16), where I0 is given by (2.17). In this relation, Ip (0) represents the current of holes at x = 0, In (w) represents the electron current at x = w, g(x) is the number of electron-hole pairs generated at point x, in unit volume and in a second, and A is the area of the structure.

This noise mainly affects the Zener diodes. It is a "white noise" type.