CRYOGENIC GaAs-FET AMPLIFIERS FOR SQUIDS

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Résumé.- Nous avons mis au point des préamplificateurs cryogéniques pour SQUIDs. Ils utilisent des transistors à effet de champ à l'arseniure de gallium. La sensibilité de l'ensemble est limitée par le bruit intrinsèque du SQUID et est 5×10^{-30} J/Hz à 500 MHz. Nous discutons les critères de conception à l'aide d'un circuit équivalent pour faibles signaux.

Abstract.- Gallium arsenide field effect transistor amplifiers for use with SQUIDs at 4.2 K in the frequency range 50 - 500 MHz have been developed. The system sensibility is limited by intrinsic SQUID noise and is 5×10^{-30} J/Hz à 500 MHz. Design criteria and practical limitations are discussed in terms of small signal equivalent circuits.

Gallium arsenide field effect transistors (GaAs-FETs) work well at 4.2 K, with the same gain and lower noise than at room temperature. They can be placed next to a SQUID, which facilitates the design of the intermediate impedance matching network, lowers its losses, and all but eliminates its noise. The FET chosen for our work was Plesseys GAT 1, which is the cheapest type available. The circuit used was the simplest possible with the FET connected in the grounded source configuration without gate bias. The drain was matched to the next 50 Ω amplifier with a quarter wavelength transmission line transformer made of a piece of 100 Ω line.

The small signal equivalent circuit of the SQUID, including matching circuits, and of the FET amplifier, is shown in figure 1. The SQUID circuit is derived and discussed in Refs. /1/ and /2/, where expressions for the forward transfer resistance r and output noise temperature T_α are given : $r = k_{sf}\sqrt{r_p \omega_p L_s'}$; $T_\alpha = \pi\alpha\phi_o^2/4k_B L$ (ω_p is the rf frequency and L is the SQUID ring inductance).

At the input of the FET amplifier we have a noise voltage generator u_{nF}^2, a noise current generator i_{nF}^2, and a resistance R_t, which is formed by the loss resistance R_{tc} of the impedance matching tank circuit in parallel with the input resistance R_{in} of the FET. According to the theory of FETs[3] u_{nF} is independent of the frequency whereas i_{nF} is given by the equation $u_{nF}/i_{nF} = R_{opt} = 1.5/\omega_p C_{gs}$, where C_{gs} is the gate to source capacitance. The voltage to current ratio is called R_{opt} because the total noise is minimized for this value of the signal source impedance. The form of the input resistance is also known : $R_{in} = (\omega_p^2 C_{gs}^2 R_s)^{-1}$, where R_s is a constant resistance, specific to the FET.

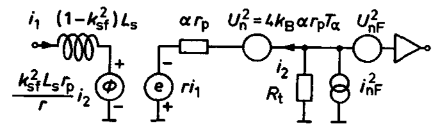

Fig. 1 :

The signal source impedance can be computed with the aid of the equivalent circuit. For the very simplest case, that of an open SQUID input ($i_1 = 0$) it is formed by αr_p in parallel with R_t. In practice one requires that the inequality $\alpha r_p \le \alpha R_t$ holds ; this is the condition for getting a non-truncated triangular pattern. As $\alpha \lesssim 0.3$ the value of the source impedance is then approximately αr_p. Whenever the stated condition allows, one chooses $\alpha r_p = R_{opt}$. Below 100 MHz we employed a thin film SQUID with an ordinary LC tank circuit whose R_{tc} multiplied by α became smaller than R_{opt} ; thus we had to make $\alpha r_p = \alpha R_{tc}$. This is equivalent to writing $k_p^2 Q_t = 1$, with k_p the coupling factor and Q_t the quality factor of the tank circuit.

Above 100 MHz we used a toroidal point contact SQUID, with a quarter wavelength transmission line transformer coupled directly to the weak link to obtain matching. R_{in} of the FET then became limiting above 500 MHz, where perforce $\alpha r_p = \alpha R_{in}$.

In figure 2 three regions are indicated, with αr_p being equal to αR_{tc}, R_{opt}, and αR_{in}, respectively. In Region 1 we have the typical values $\alpha = 0.2$

and Q_t = 50. In Regions 2 and 3 R_{opt} and R_{in} were computed using values of C_{gs} and R_s determined by connecting quarter wavelength resonators of known length to the input of the FET amplifier and measuring the resonant frequencies and the Q-values (results : C_{gs} = 2pF, R_s = 30 Ω).

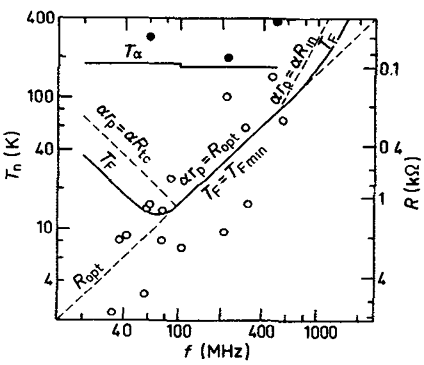

Fig. 2 :

R_{opt} was also measured directly by recording the noise spectrum from the amplifier with a resonant circuit coupled to the input. u_{nF} is then obtained from the part of the spectrum far below resonance, and equals, above 50 MHz, 0.7 nV in a 1 Hz bandwidth. i_{nF}, and thus also R_{opt}, can be deduced from the noise at the resonance frequency. The measured values of R_{opt} are plotted as open circles in figure 2.

Matching in Regions 2 and 3 requires knowledge of r_p for the quarter line transformer system. It can be computed assuming $\omega_p L$ to be the relevant value before impedance matching (L is the SQUID inductance). A quarter wave line of impedance Z_o and with coupling coefficient k_p to the weak link then transforms this value to $r_p = Z_o^2/K_p^2\omega_p L$. In Region 2 the same value for Z_o is optimal throughout : we used a 20 Ω line.

The noise voltage at the FET input can be computed from figure 1. With $\alpha r_p \ll R_t$ and $i_1 = 0$ it becomes $u_n^2 = 4k_B\alpha r_p T_\alpha B + u_{nF}^2 + (i_{nF}\alpha r_p)^2 = 4k_B\alpha r_p B(T_\alpha + T_F)$, where we define the FET amplifier noise temperature $T_F = (u_{nF}^2/\alpha r_p + i_{nF}^2\alpha r_p)/4k_B$ (k_B is Boltzmann's constant and B is the bandwidth). The corresponding input energy noise is $E_n = u_n^2 L_{in}/2r^2$, where L_{in} is the input inductance. Approximating L_{in} with L_s and using the theoretical expression for r this can be written $E_n = 2k_B\alpha B(T_\alpha + T_F)/k_{sf}^2\omega_p$. T_F, and also E_n, is minimized for $\alpha r_p = R_{opt}$; the corresponding value we call $T_{Fmin} = u_{nF}^2/2k_B R_{opt} B$.

T_{Fmin} is inversely proportional to R_{opt}. The values corresponding to the unfilled points of figure 2 can be read from the left of the figure ; the same is true for the theoretical line along the diagonal. In Region 2 T_F for the SQUID system is equal to T_{Fmin}, but in Regions 1 and 3 it is higher as the source impedance presented to the SQUID is below optimum. The expected value of T_F is indicated in the figure with a solid line.

The intrinsic noise temperature T_α of the SQUID has also been indicated in figure 2. The upper solid line shows the theoretical value and the filled circles the measured ones ; the computed values of T_F have been subtracted from the latter. For the thin film SQUID the total measured energy noise at 60 MHz was 50 × 10^{-30} J/Hz, and for the point contact device at 500 MHz 5 × 10^{-30} J/Hz.

A further check of the data was obtained by cooling the thin film SQUID to 0.2 K to eliminate its noise. The total energy noise was then determined solely by the FET contribution, which in Region 1 is independent of temperature. As expected E_n improved by one order of magnitude to 5 × 10^{-30} J/Hz.

References

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