ULTRA-LOW-NOISE, HIGH-IMPEDANCE PREAMP FOR CRYOGENIC DETECTORS

Indexing terms: Semiconductor devices and materials, Detector circuits

A preamplifier design is presented which is based on a common-drain JFET input. The midband noise performance is $E_n = 0{\cdot}42\ \mathrm{nV/Hz^{1/2}}$, $I_n = 2{\cdot}8\ \mathrm{fA/Hz^{1/2}}$. The circuit has considerably less input capacitance than comparably noisy common-source amplifiers. It is particularly useful for preamplification of 0·1 to 10 MHz signals from liquid-helium-cooled radiation detectors.

Introduction: Certain liquid-helium-cooled semiconducting materials make the most sensitive radiation detectors for the far-infra-red region of the spectrum. A few examples are the InSb Putley-mode detector, the Ge photoconductor and the GaAs photoconductor. All three display high dynamic impedance, relatively large bandwidth and very little noise because of their low operating temperature. These characteristics make it difficult to design a preamplifier that causes negligible degradation of the detector signal/noise ratio over the entire detector bandwidth. This letter presents a relatively simple room-temperature preamp design that satisfies both the low-noise and wideband requirements for the InSb Putley-mode detector, which has a dynamic impedance of about 1 kΩ and a bandwidth of about 5 MHz.

Low-noise preamplification of high-impedance detectors is usually accomplished with field-effect transistors. Silicon JFETs are preferred for frequencies below about 10 MHz because they display much less $1/f$ noise in this region than the alternative devices, Si MOSFETs or GaAs MESFETs. Under optimum DC bias conditions for low-noise operation, the gate-source capacitance C_{gs} of a JFET is typically much greater than the gate-drain capacitance C_{gd}. Despite this fact, most low-noise preamp designs configure the JFETs in the common-source configuration. One successful design, the 'mismatched pair',[1] has a common-emitter second stage with negative feedback to decrease the load impedance of the FET, thereby decreasing the gain and the concomitant Miller effect. Another well known design, the 'cascode',[1] uses a common-base second stage, again to reduce the Miller effect at the FET. Both designs present the full value of C_{gs} and at least one unit of C_{gd} to the input.

Design: This letter presents a design that has much less input capacitance than room-temperature mismatched pair or cascode amplifiers of comparable noise. The trick is the use of a common-drain JFET at the input combined with a superior-quality bipolar transistor in the second stage. With the bipolar transistor configured common-emitter and with a large source bias impedance, it is not hard to achieve a voltage gain near unity in the first stage, thereby bootstrapping out most of C_{gs}. The only difficulty is in finding a bipolar transistor that has a very low noise figure when coupled to the small output dynamic resistance of the follower, $Z \sim 1/g_m$, where g_m is the FET transconductance.

The schematic diagram of the preamp design is shown in Fig. 1. It consists of N parallel FET-bipolar pairs, where N is chosen to make the noise factor suitably small. Note that T_2 has a small degree of emitter degeneration. This enhances the bandwidth and improves the performance of the FET source-follower. The signal currents from the N pairs are summed at the emitter of a common-base transistor third stage and the output voltage is generated across the load resistor R_8. Neglecting the noise from bias resistors and stages after T_2, the theoretical input RMS noise generators at midband frequencies are found to be[2]

$$E_n \simeq N^{-1/2}\left(\overline{E_1^2} + 4kT(R_b + R_5) + \frac{2eI_c}{\beta g_m^2} + \frac{2(kT)^2}{eI_c}\right)^{1/2} \quad (1)$$

$$I_n \simeq (N2eI_g)^{1/2} \quad (2)$$

where E_1 is the FET RMS noise voltage, k is Boltzmann's constant, T is the transistor operating temperature, I_g is the FET gate leakage current, and R_b, I_c and β are the bipolar transistor base parasitic resistance, collector current and DC current gain, respectively. In deriving eqn. 1 it has been assumed that the voltage gain of the first stage is unity. The total input capacitance is then

$$C_i \simeq NC_{gd} \quad (3)$$

At midband frequencies, E_1 represents channel thermal noise, and can be approximated by the well known expression $\overline{E_1^2} \simeq 2/3(4kT/g_m)$.[3] The last two terms of eqn. 1 represent the base-emitter junction shot noise and the base-collector junction shot noise, respectively. It is simple to show that the contribution of these two terms is minimised for a collector current $I_c = kTg_m\beta^{1/2}/e$. The resulting equivalent input noise voltage is

$$E_n \simeq N^{-1/2}\left(\frac{2}{3}\frac{4kT}{g_m} + 4kT(R_b + R_5) + \frac{4kT}{g_m\beta^{1/2}}\right)^{1/2} \quad (4)$$

This expression shows clearly that if $R_b + R_5 \ll 1/g_m$ and $\beta \gg 1$, then the total noise is degraded little by the second stage.

Performance: An eight-pair version of this circuit was constructed using the Siliconix J309 for the first stage. Under the given operating conditions, this device has the following characteristics: $g_m \simeq 0{\cdot}014$ S, $C_{gd} \simeq 2{\cdot}5$ pF, $C_{gs} \simeq 6$ pF, $E_1 \simeq 1{\cdot}1\ \mathrm{nV/Hz^{1/2}}$ and $I_1 \simeq 1{\cdot}0\ \mathrm{fA/Hz^{1/2}}$ at $I_d = 9$ mA. The second-stage bipolar transistor is an R Ω 2SD786 which has the following characteristics: $R_b \simeq 4\ \Omega$, $\beta \simeq 200$ and $f_T \simeq 60$ MHz at $I_c = 5$ mA. The other circuit elements are as follows: T_3 is a 2SB737, $R_1 = 750\ \Omega$, $R_2 = 1{\cdot}3$ kΩ, $R_3 = 1{\cdot}2$ kΩ, $R_4 = 2{\cdot}4$ kΩ, $R_5 = 15\ \Omega$, $R_6 = 1{\cdot}2$ kΩ, $R_7 = 750\ \Omega$, $R_8 = 150\ \Omega$, $C_1 = C_3 = 1\ \mu$F, $C_2 = C_4 = 0{\cdot}01\ \mu$F ($C_2$ is preferably a chip capacitor), $C_5 = 0{\cdot}1\ \mu$F, $C_6 = 1\ \mu$F and $L = 33$ mH. The measured amplifier performance is $E_n \simeq 0{\cdot}42\ \mathrm{nV/Hz^{1/2}}$ and $I_n \simeq 2{\cdot}8\ \mathrm{fA/Hz^{1/2}}$ at 1·0 MHz and $C_i \simeq 28$ pF. This voltage noise is only about 10% higher than that expected from eqn. 4. The discrepancy is due mostly to the fact that the actual voltage noise contribution of the J309 is larger than the theoretical prediction used in eqn. 4. When operating into a reasonably high input impedance ($\gtrsim 1$ kΩ) video amp, the midband voltage gain of this preamp is 46. The lower 3 dB rolloff frequency is 100 kHz. For source impedances $\lesssim 400\ \Omega$, the upper 3 dB rolloff frequency is 15 MHz. This rolloff is caused by the rather large emitter diffusion capacitance of the 2SD786s.

This design can be easily adapted to suit other difficult preamp applications. One adaptation would be a one-pair version for a very-high-impedance (~ 5 kΩ) cryogenic detector like liquid-helium-cooled germanium. If the detector were coupled to such a preamp with triax cable, then the cable capacitance could be bootstrapped out by connecting the centre shield to the source lead of T_1. This would avoid the difficulty of making a liquid-helium-cooled FET preamp close to the detector. However, one would probably want to use both a FET with a much larger room-temperature g_m/C_{gd} ratio than the J309 and a second stage with a higher f_T than the 2SD786 to increase the bandwidth.

Conclusions: We have presented a room-temperature preamp that has midband noise performance $E_n \simeq 0{\cdot}42\ \mathrm{nV/Hz^{1/2}}$ and

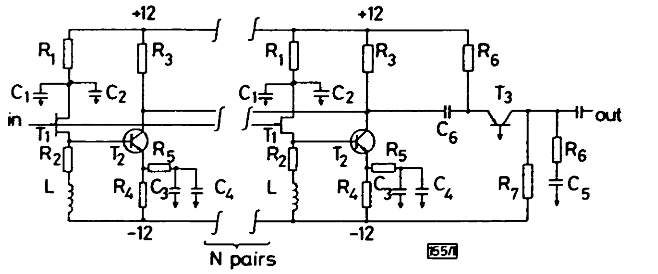

Fig. 1 *Schematic diagram of low-noise preamp based on common-drain JFET input*

Component values and performance characteristics are given in the text

$I_n \simeq 2.8$ fA/Hz$^{1/2}$, and a total input capacitance of only 28 pF. This capacitance is much less than that displayed by previous room-temperature JFET preamps of comparable noise.

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HIGH-POWER SINGLE-MODE OPTICAL-FIBRE COUPLING TO InGaAsP 1·3 μm MESA-STRUCTURE SURFACE-EMITTING LEDs

Indexing terms: Optical communications, Optical connectors and couplers

High-power single-mode optical-fibre coupling to LEDs has been achieved by novel mesa-structure InGaAsP 1·3 μm surface-emitting LEDs. A −26·7 dBm (2·1 μW) fibre-coupled power has been obtained with 210 MHz optical −3 dB modulation bandwidth at 23°C 50 mA current. The 140 Mbit/s transmission feasibility over a single-mode optical fibre has been studied.

InGaAsP 1·3 μm-wavelength light-emitting-diodes (LEDs) are reliable, inexpensive alternatives to laser diodes in intermediate-length-range optical communication systems, such as local-area networks and subscriber loops. It is attractive to use single-mode optical fibre (SMF) instead of multimode optical fibre in these systems, because of low light attenuation and wide bandwidth for SMF. Very recently, LEDs have been recognised as possible sources for SMF transmission.[1–3] SMF-to-LED coupled power is an important factor, which limits SMF-LED system performance. Although surface-emitting LEDs have reliability and temperature stability advantages over edge-emitting LEDs, the reported SMF-LED coupled power for surface-emitting LEDs was about −35 dBm,[1,3] which is much less than for edge-emitting LEDs, which ranges from −22 to −28 dBm.[2,3] This letter reports high-power SMF to surface-emitting LEDs coupling achieved by novel mesa-structure InGaAsP 1·3 μm surface-emitting LEDs. A −26·7 dBm coupled power, which was comparable to edge-emitting LED power, has been obtained at 23°C DC–50 mA current. The feasibility has also been discussed for 140 Mbit/s transmission over SMF.

The LEDs developed have a small-diameter circular mesa to improve lateral carrier confinement, resulting in high coupling efficiency. The LED structure is shown in Fig. 1. LEDs were made on *n*-InP substrate with liquid-phase-epitaxial layers of 4 μm thick *n*-InP:Sn, 2 μm-thick undoped InGaAsP active layer, 1 μm-thick *p*-InP:Zn and 0·8 μm-thick *p*-InGaAsP:Zn. Mesas 20 μm in diameter and 5 μm high were formed by chemical etching using Br-methanol-H_3PO_4 solution. The epitaxial layer surface, except for the mesa top, was covered with SiO_2. An Au/Zn contact was formed on the mesa top. A monolithic lens, covered with Si_3N_4 antireflection coating, was formed on the *n*-InP substrate surface.

Since lateral carrier confinement was efficiently achieved by mesas, the light-intensity profiles for mesa LEDs were uniform without Gaussian spreading, which was typically observed in Zn-diffusion- or SiO_2-isolated conventional structure LEDs. This gave rise to high coupling efficiency between the LED

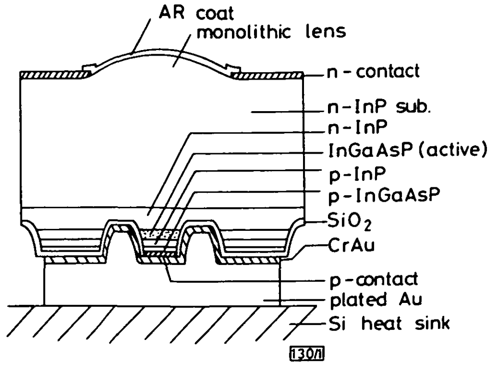

Fig. 1 *InGaAsP 1·3 μm mesa-structure surface-emitting LED diagram*

and SMF. The coupling efficiency to 10 μm-core SMF has been found to be −27 dB for spherical-ended graded-index rod lens coupling and −28 dB for butt coupling. These values were about 7 dB higher than recently reported values for Zn-diffusion isolated surface-emitting LEDs with similar emitting region diameter (20 μm).[3] As a result, lens-coupled power of −26·7 dBm (2·1 μW) into SMF has been obtained at 23°C DC–50 mA current as shown in Fig. 2. SMF butt-coupled

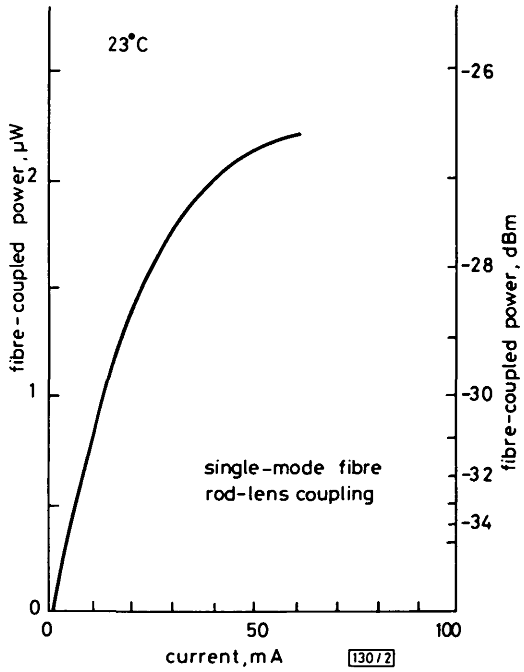

Fig. 2 *Current against single-mode optical-fibre coupled power characteristics*

power was −28·1 dBm at DC −50 mA. The peak wavelength and spectral halfwidth were 1·30 μm and 120 nm, respectively. The obtained coupled power was more than six times (8 dB) as high as that for reported surface-emitting LEDs[1,3] and was comparable to edge-emitting LEDs coupled power.[2,3]

SMF-LED coupled power temperature dependence is shown in Fig. 3. The temperature coefficient for coupled power, dP_f/dT, was found to be −0·030 dB/deg. Therefore, 20 to 50°C power difference was less than 1 dB. A −27·5 dBm SMF-coupled power has been obtained at 50°C DC–50 mA current. This small temperature coefficient for the mesa LED would be an important advantage over other sources, because transmission installed ambient temperature would vary widely.

Transmission feasibility over SMF, using the mesa-structure surface-emitting LEDs, would be of great concern. Optical −3 dB modulation bandwidth for the mesa LED has been found to be 210 MHz at 50 mA, as shown in Fig. 4. Therefore, a 140 Mbit/s bit rate was considered. The −30 dBm average coupled power and −43 dBm[2] assumed receiver average-power sensitivity will remain in the 13 dB loss budget.