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A Monolithic Common-Collector Front-End Optical Preamplifier

MARTIN J. N. SIBLEY, RODNEY T. UNWIN, DAVID R. SMITH, BRUCE A. BOXALL, AND RICHARD J. HAWKINS

Abstract—A monolithic transimpedance preamplifier has been developed having a common-collector cascode configuration with shunt feedback, using an advanced bipolar IC process. The measured sensitivity was $-35.0 \text{ dBm}$ at 140 Mbit/s for an error rate of $10^{-9}$ and a p-i-n photodiode responsivity of 0.5 A/W.

In bipolar optical preamplifiers it is common practice to employ a common-emitter front end or, where Miller capacitance is to be eliminated, a cascode input [1]. These configurations do, however, have a disadvantage in that the preamplifier 3-dB bandwidth depends on the base-emitter capacitance of the front-end transistor ($C_{EB}$). In addition, the base-spreading resistance ($r_{bb}$) can significantly affect the preamplifier transfer function, and may even result in a two-pole frequency response if $r_{bb}$ is high enough [1]. Both of these disadvantages are overcome, together with the elimination of Miller capacitance, if a common-collector front end is employed. A previous paper [2] has demonstrated the usefulness of this type of preamplifier input in obtaining a receiver with a wide-band response. A common-collector common-emitter feedback design was constructed in discrete component form and was found to be suitable for 140-Mbit/s operation.

This paper describes a directly coupled preamplifier based on a common-collector, cascode design which is also suitable for a 140-Mbit/s receiver. The complete receiver is shown in Fig. 1 and the components shown within the dotted box have been fabricated in monolithic IC form at BTRL. This design, unlike the earlier one [2], has a single-pole response which would also enable the receiver to operate at bit rates in excess of 140 Mbit/s by employing simple equalization techniques.

The design was fabricated in monolithic IC form in order to produce a low-cost optical receiver for high-speed data bus systems, and for optical local-area networks. The monolithic IC preamplifier has given reduced stray capacitances, resulting in an improved frequency response. In addition, the circuit has been fabricated using a proven bipolar IC process to give a high reliability compared to conventional p.c.b. or hybrid designs.

The cascode stage ($T_2$ and $T_3$) is biased by an emitter follower ($T_4$) fed from the diode chain $T_5$, $T_6$, and $T_7$. The emitter currents in this part of the circuit are designed to be 2 mA to ensure identical $V_{be}$ values. The voltage gain of the cascode may be externally adjusted by varying $R_C$. Resistor $R_1$ ensures that the cascode bias current (and hence the second-stage open-loop voltage gain) is close to the design value regardless of the exact $V_{be}$ values of the transistors.

The closed-loop pole due to the cascode stage is sufficiently high (220 MHz) so as not to affect the preamplifier 3-dB bandwidth. Thus the closed-loop bandwidth is governed by a single open-loop time constant given by (1).

$$r_{in} = (R_{in} || R_f) C_{in}$$ (1)

where

$$R_{in} \text{ open-loop input resistance of the receiver,}$$

$$r_n \text{ element in the hybrid } - \pi \text{ transistor model,}$$

$$C_{in} = C_d + C_s + C_{st} + C_f,$$

$$C_s \text{ bond pad to substrate capacitance.}$$

We also define $A_1$ and $A_2$ as the first- and second-stage open-loop mid-frequency voltage gains, respectively, and $A_0$ as the closed-loop mid-frequency voltage gain between $T_1$ base and $T_3$ collector. The closed-loop transimpedance $Z_e(s)$ between these nodes is given by (2), where $A_0$ can be taken to equal...
TABLE I

<table>
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<th>Design Parameters</th>
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\[ Z_c(s) = \frac{-A_0 R_{\text{eff}}}{1 + s R_{\text{eff}} (C_d + C_s + C_{c1} + (1 + A_0)C_f)} \]

where \( R_{\text{eff}} = R_{\text{bb}} || (R_f / (1 + A_0)) \).

By using the design details given in Table I the preamplifier -3-dB bandwidth is calculated from (2) to be 107 MHz. As a comparison, the closed-loop transimpedance for an equivalent cascode input design, having a single pole response, is given by

\[ Z_c(s) = \frac{-A_0 R_{\text{eff}}}{1 + s R_{\text{eff}} (C_d + C_s + C_{c1} + C_{c1} + (1 + A_0)C_f)} \]

In general, \( C_{c1} \) has the effect of reducing the -3-dB bandwidth considerably.

At optimum bias, the S/N ratio at the output of the predection filter is at a maximum (3). In this design, \( T_1 \) has a base current of 3.4 μA as opposed to an optimum value of 2.5 μA. This only incurs a small noise penalty particularly as the thermal noise from \( R_f \) is dominant in determining the receiver sensitivity.

The emitter length of \( T_2 \) is twice that of \( T_1 \), and this results in a relatively low base spreading resistance of 153 Ω. This value of \( r_{bb} \), together with the second stage shot noise, degrades the sensitivity by 0.3 dB. This degradation could be reduced by optimizing the IC process for lower values of \( r_{bb} \).

The advanced bipolar process uses a double diffused structure with a 0.15-μm basewidth. The small feature sizes (3-μm emitter, 2-μm base contacts, 1.5-μm recut emitter contacts, and 2.4-μm-wide titanium-gold metallization) were all defined by electron-beam lithography [4]. Care was taken in routing the metallization tracks within the IC in order to minimize the capacitance to ground at the input node. The IC was mounted in an 18-pin chip carrier, and the complete receiver constructed on PCB using chip resistors and an HP 5082-4205 Si p-i-n diode having a responsivity of 0.5 A/W.

The p-i-n was irradiated by an 850-nm GaAlAs laser and the bandwidth calculated from rise-time measurements was 100 MHz. The optical dynamic range was measured to be 20 dB.

Fig. 2 compares the computer predicted and measured transimpedance versus frequency responses, and also shown are the spectral densities of the input equivalent noise current (\( S_{\text{eq}}(\omega) \)). The measured frequency response was obtained by irradiating the p-i-n with an unmodulated high-intensity edge-emitting GaAlAs LED (such that the p-i-n diode shot noise was far in excess of the preamplifier noise). Under this condition, the output of the preamplifier, as measured using a spectrum analyzer, corresponds to the transimpedance versus frequency response. As can be seen from Fig. 2, the bandwidth obtained by this method correlates well with the bandwidth found from the rise-time measurement. The input equivalent noise current spectral density was found by dividing the measured output noise voltage by the measured transimpedance.

In conclusion, we have demonstrated a monolithic IC preamplifier based on a common-collector cascode configuration. The receiver has a single-pole frequency response making subsequent equalization and operation beyond 140 Mbit/s possible. The receiver has an optical dynamic range of 20 dB and a measured sensitivity of -35.0 dBm at 140 Mbit/s.

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REFERENCES


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David R. Smith was born in England in 1949. He received the B.A. and M.A. degrees in natural sciences from Christ's College, Cambridge University, England in 1971 and 1976, respectively. In 1971, he joined the British Post Office Research Department (now known as British Telecom Research Laboratories, Martlesham Heath, England) where he has been engaged in research on optical-fiber systems and components. He is presently Head of the Optical Receivers and New Optical Components Group.

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After a further period at Southampton as Junior Research Fellow in the Department of Electronics he joined the Microelectronics Division of British Telecom Research Laboratories, Ipswich, England, where he is now head of the bipolar IC design group. He is the author of a number of papers on low and high-frequency noise and the measurement and modeling of high-frequency transistors.