AN ABSTRACT OF THE THESIS OF

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David J. Allstot

A GaAs optical receiver has been designed. In this circuit, a source follower interfaces the photodiode to the main amplifier and is used to improve the frequency response and to supply the necessary bias voltage to the main amplifier. A common-source (CS) amplifier with an improved "self bootstrapped" load is used to obtain high voltage gain. Finally, the output voltage of the amplifier is level shifted by a source follower to match the next stage. In this thesis, a transimpedance (TZ) amplifier and a high impedance (HZ) amplifier are presented and compared. Using a one-micron recessed-gate depletion-mode GaAs MESFET technology, the TZ amplifier characteristics are 29.3 dB gain, 1.5 GHz bandwidth, and 2.55 $pA/\sqrt{Hz}$ input equivalent thermal noise current with a 3 kΩ transimpedance. Moreover, the characteristics of the high

impedance amplifier with a 1 kΩ front-end input load resistance are a 29.5 dB gain, 1.1 GHz bandwidth, and 5.03 $pA/\sqrt{Hz}$ input equivalent thermal noise current at 100 MHz.

# Design of GaAs Monolithically Integrated Optical Receiver Amplifier

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# DESIGN OF GaAs MONOLITHICALLY INTEGRATED OPTICAL RECEIVER AMPLIFIER

## I. INTRODUCTION

One technique for receiving and repeating optical signals is to transform the optical signal into an electrical signal using a photodetector, and to amplify the electrical signal by a diode-preamplifier approach. Another approach is direct optical amplification [1] which can attain the objectives of high gain and high speed. However, more studies on the materials and device structure of direct optical amplifiers are needed. The diode-preamplifier solution is popular because it is based on more mature semiconductor technologies, and therefore has greater probability of immediate application to optoelectronic systems.

The optical receiver performance is a function of both the photodetector and the receiver amplifier. In this thesis, GaAs MESFET devices are used for the amplifier because they can be fabricated with extremely low capacitance and high transconductance. Moreover, a semi-insulating (SI) GaAs schottky contact photodetector is integrated monolithically with the GaAs amplifier. For the photoreceiver in a high-speed optical communication and data-processing system, the optoelectronic integrated circuit is attractive and significant because the monolithic integration has the capability of reducing parasitic reactance which predominantly restricts the speed and noise performance in photoreceiver circuits composed of discrete elements [2]-[3]. The GaAs interdigitated schottky contact photoconductor is extremely suitable for use in such integration due to its potential compability with most GaAs circuit processes and its simple structure.

High speed and high sensitivity are the important requirements of optical front ends. In this work, high speed is acheived by using a source follower to interface the photodiode and the amplifier to reduce the Miller capacitance and to increase the input impedance. The source follower is also used to supply the necessary bias voltage to the amplifier. In the main amplifier, high gain is attained by a one stage common-source amplifier using an improved "self-bootstrapped" load [4]. Previously reported GaAs high gain amplifiers [5]-[7] used multistage constructions with a gain range from 26 dB to 42 dB. To avoid the bandwidth degradation and large chip size of multiatge amplifiers, the circuit in this work obtains the objectives of high gain and small size by using one stage amplifier. Typical optical receiver amplifiers are designed by using either the high impedance amplifier or the transimpedance amplifier. Using the one stage amplifier, a transimpedance amplifier and a high impedance amplifier are presented by the design principles of receiver amplifier.

The schottky contact detector is described in the next chapter and the design considerations of the main circuit are described in chapter III. Two receiver amplifiers using the same main circuit and different principles, the high-impedance and transimpedance amplifiers [8], are described and compared in chapter IV. The circuit analysis for both the receiver amplifiers is given in chapter V and a conclusion is given in the final chapter.

# II. SCHOTTKY CONTACT PHOTOCONDUCTIVE DETECTOR

The optical receiver is composed of a photodetector and the receiver amplifier. A good photodetector will alleivate the design requirements on the amplifier. For improving the speed and noise performance, the GaAs schottky contact photodiode (SCD) which is closely compatible with GaAs IC processing is monolithically integrated with a GaAs amplifier. Several researchers have studied and reported the monolithic P-i-N/FET photoreceivers [9]-[10]. However, the P-i-N photodiode and the FET are not compatible in device structure and fabrication processes. The interdigitated SCD which is a planar photodiode [11]-[12] is much more suitable for the monolithic integration of an optical receiver than the conventional P-i-N diode having a vertical structure.

The SI-GaAs SCD is fabricated by directly depositing Schottky electrodes onto a semi-insulating (SI) GaAs subatrate [13]. A cross sectional view of the semi-insulating GaAs schottky contact detector is shown in fig. 2-1. In the thesis, two patterns which have been studied and measured by H. C. Yang [14] are used: (1) an interdigitated structure with 5 um spacings and 2 um lines, and (2) an interdigitated structure with 2 um spacings and 2 um lines. There are four interdigitated fingers in the first

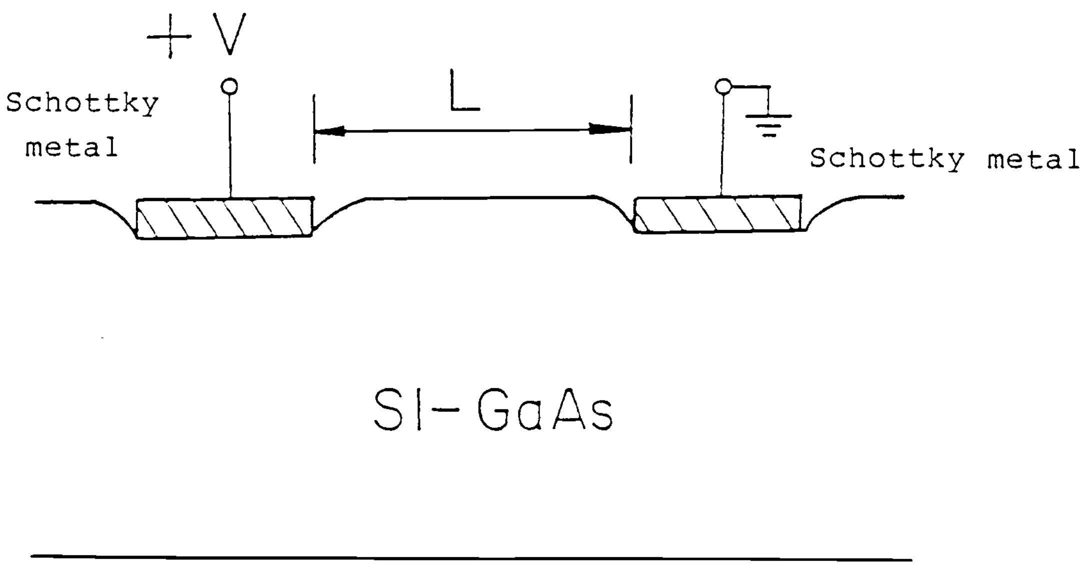



Fig. 2-1 A cross sectional view of the SI-GaAs SCD [14].

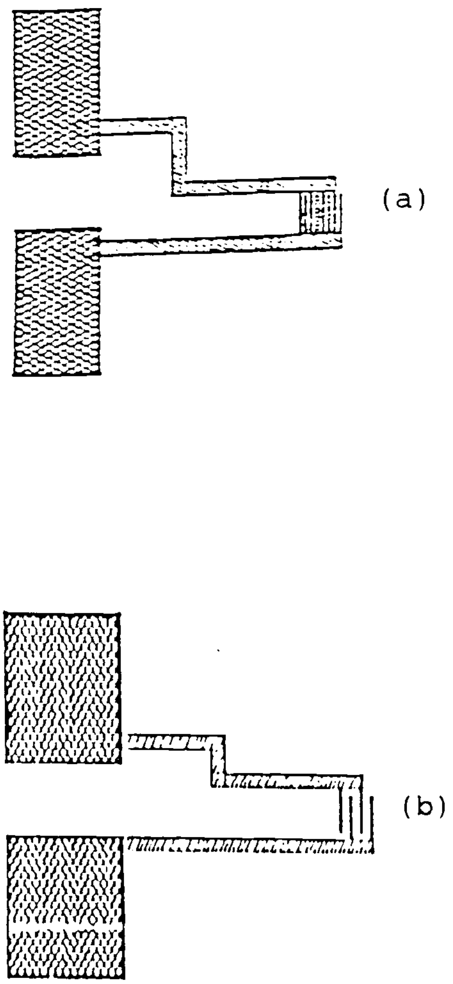



Fig. 2-2 Two patterns of the SI-GaAs SCD

(a) 2 um spacings and 2 um lines, and

(b) 5 um spacings and 2 um lines.

pattern and eight fingers in the second one. All interdigitated finger lengths are 25 um. The two patterns are shown in fig. 2-2.

For simulation, a photodiode is represented with circuit elements by a current source in parallel with a capacitor which depends on the functional area. In fig. 2-3, the capacitor (Cd) represents the detector junction capacitance. Carriers generated within the detector are represented by the current, IS.

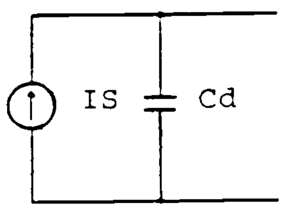



Fig. 2-3 The equivalent circuit of the photodiode.

# III. DESIGN CONSIDERATIONS OF THE AMPLIFIER

Using the diode-preamplifier approach, the optical power that impinges upon the optical detector is converted to an electrical current which must be amplified and processed electronically. In most cases, the current generated by the detector is very small and is subject to corruption by amplifier noise. Therefore, the low input noise requirement of the amplifier is necessary for error-free data communication systems.

For a high speed optical receiver, wide bandwidth and high optical sensitivity are the most significant requirements. The amplifier sensitivity depends on the relative magnitude of the various receiver noise sources. Archambaul [5] described the noise currents and distinguished them as:

1. Diode noise current;
2. Thermal noise current of the input resistance;
3. FET noise sources;
   a. Channel thermal noise [15] and gate noise [16];
   b. 1/f noise current;
   c. Gate leakage noise current.

At the high frequencies under consideration, the flicker noise can be neglected. Furthermore, the thermal noise current of the input resistance is the dominant noise current source. Therefore, the gate widths of devices are decided by the SPICE simulation of the input equivalent current noise (thermal noise) and frequency response. According to these principles, an optical amplifier is designed. For the GaAs MESFETs, all gate lengths are 1 um and all channel lengths are 3 um.

3.1. Main amplifier

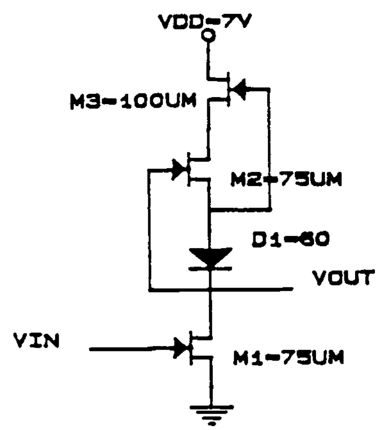



Fig.3-1 The common - source amplifier with an improved " self-bootstrapped " load.

A single stage amplifier is used in this circuit. It is a common source amplifier with an improved "self-bootstrapped" load. A schematic diagram of the amplifier is shown in fig. 3-1. In the load, D1 is used to supply suitable voltage drop between the gate and the source of M2. Therefore, M2 can exhibit current saturation at lower drain-source voltages. By proper scaling of device widths, all three MESFETs can be biased into the saturation region. The higher gain is achieved because the output impedance of the load is enhanced by a factor of about gm/gds, which is typically about 10. The detailed circuit analysis is given in chapter V.

In this amplifier, the appropriate values of the gate widths are chosen by simulation. M3 is 100 um wide and M2 and M1 are 75 um wide. The simulated results are shown in figs. 3-2 and 3-3. For small gate width, large corner frequency is obtained. This is because the corner frequency (fc) is degraded due to the large input capacitance for a large gate width. In fig. 3-3, the noise performance is improved by increasing the gate width.

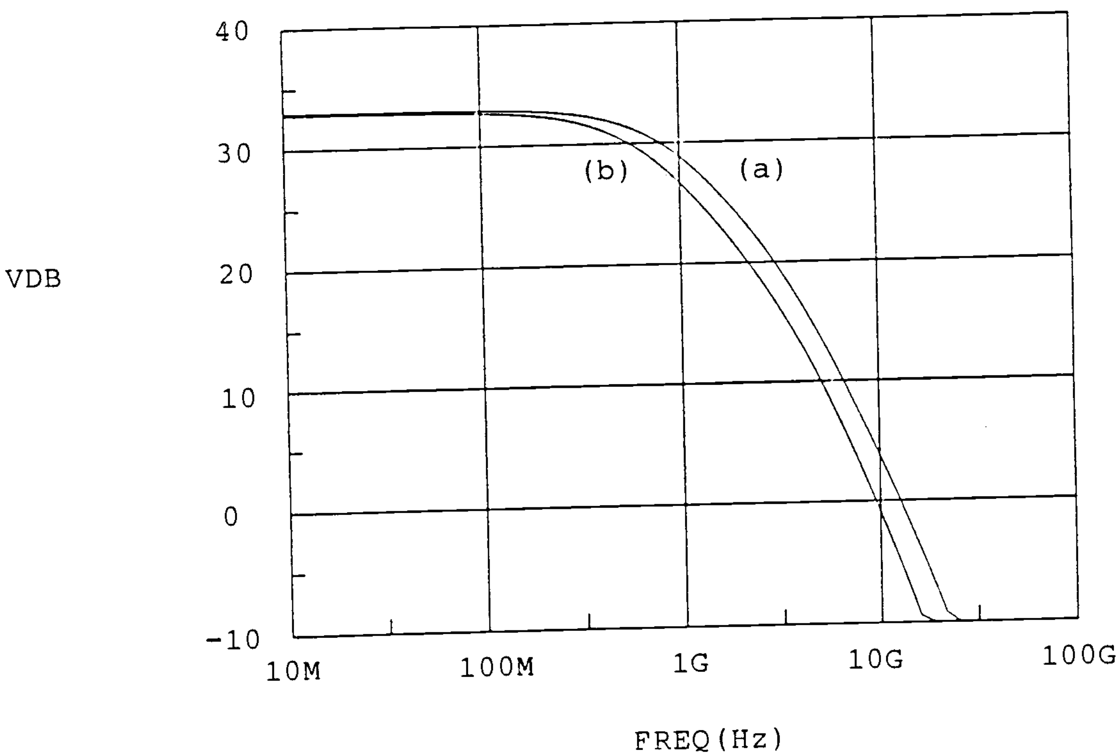



Fig. 3-2 The frequency response of the main amplifier with (a) M1=75, M2=75, M3=100um, and D1=60; (b) M1=200, M2=200, M3=400um, and D1=160.

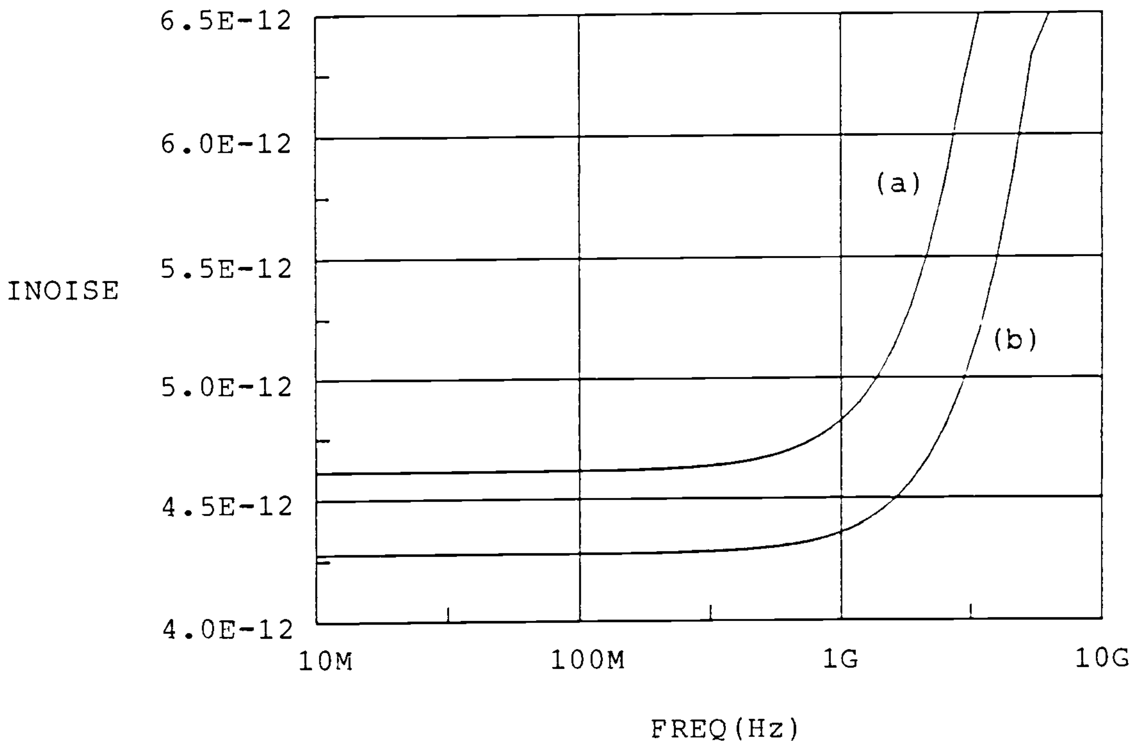



Fig. 3-3 The input equivalent thermal noise current of the main amplifier with (a) M1=75, M2=75, M3=100μm, and D1=60; (b) M1=200, M2=200, M3=400μm, and D1=160.

## 3.2. Input stage

An input stage MESFET, M5, and a resistor, R2, serve to reduce noise, together with the elimination of the Miller capacitance resulting from the gate-drain junction capacitance of the MESFET, M1. Furthermore, the input impedance becomes higher. Another purpose of using the source follower is to supply the necessary bias voltage to the main amplifier. Replacing a MESFET, a resistor is used as the load of source follower. The resistor contributes only thermal ($4KT\Delta f/R$) noise power, while the MESFET has additional FET noise contributions.

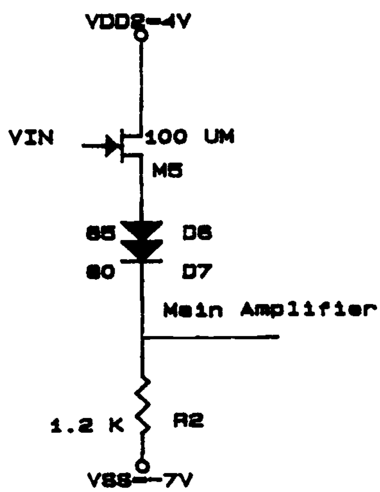



Fig. 3-4 The input stage of the receiver amplifier.

In the input stage of fig. 3-4, MESFET M5, and resistor R2 are also determined by taking into account the noise reduction and wideband frequency response. These device widths are optimized by SPICE simulation. M5 is 100 um wide and R2 is equal to 1.2 kΩ. A -0.74 volts DC output voltage is yielded by the source follower and supplied to the main amplifier.

## 3.3. Output stage

The output of the main amplifier is connected to a buffer-level shift circuit which permits smaller capacitive loading, and therefore increased bandwidth of operation. Level shifting with four diodes allows the next stage to be directly coupled with the correct input gate voltage. In the output stage of fig. 3-5, MESFET M4 is 100 um wide and resistor R1 is 700 Ω to obtain 0 V DC output voltage.

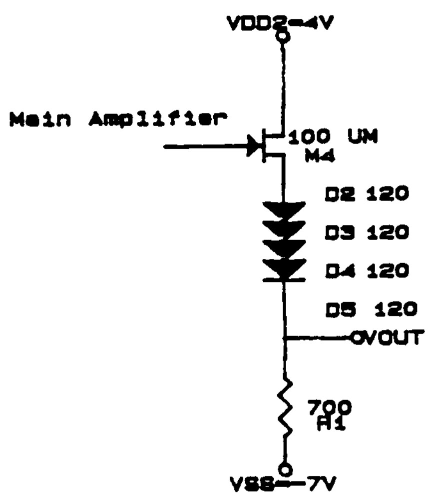



Fig. 3-5 The output stage of the receiver amplifier.

In the SPICE simulations, a 1 kΩ input load resistance and a 0.1 Pf diode capacitance are used. The amplifier is shown in fig. 3-6 and the performance is summarized below:

Gain of main amplifier = 33.0 dB

Bandwidth of main amplifier = 0.8 GHz

Overall gain of amplifier = 29.5 dB

Bandwidth of amplifier = 1.1 GHz.

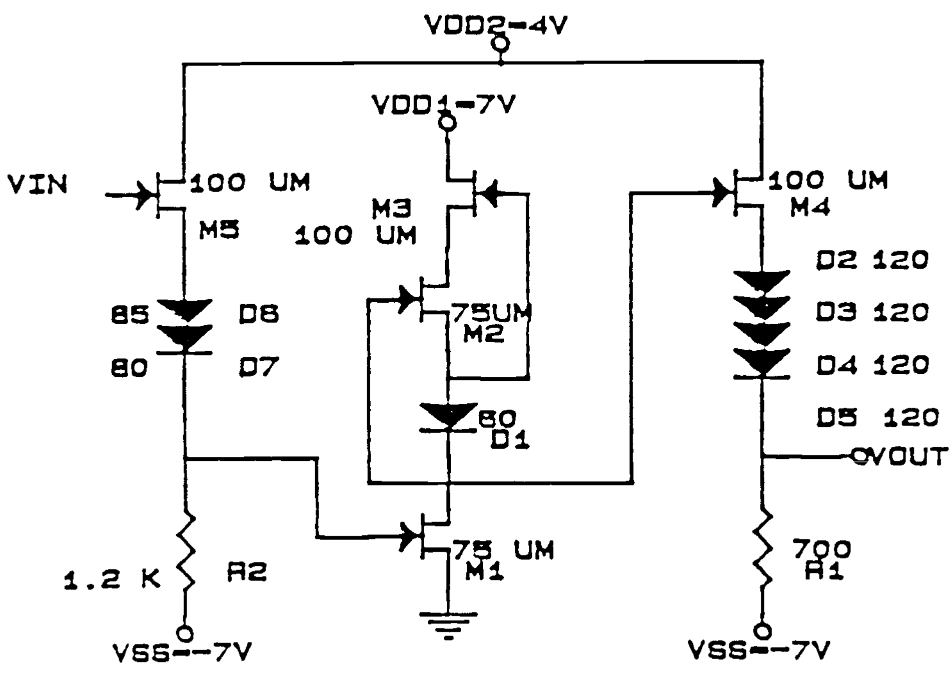


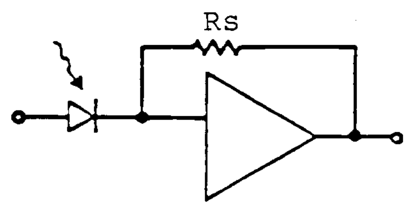

Fig. 3-6 The main scheme of receiver amplifier. All gate lengths are 1 um and all channel lengths are 3 um.

# IV. COMPARISON OF TRANSIMPEDANCE AND HIGH IMPEDANCE AMPLIFIERS

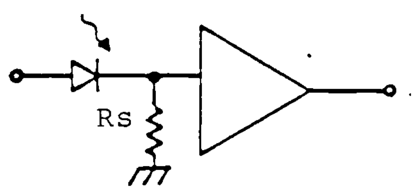
The main scheme of the receiver amplifier is described in the previous chapter. Typical optical receiver amplifiers are designed using either the High impedance (HZ) amplifier or the Transimpedance (TZ) amplifier.

In most cases, the transimpedance approach offers less flexibility with respect to DC - level adjustment between stages since DC - coupling is preferred. It also requires careful consideration of the phase margin and feedback path length to prevent oscillation. However, the advantages over the HZ type front - end circuit are a wider bandwidth, a wider dynamic range and a flat frequency response resulting in less complex equalization to obtain the same noise performance as with a HZ front - end amplifier.

The design principles of receiver amplifier are shown in the fig. 4-1. The photodetector is represented with a 0.1 PF capacitance and a ideal current source in all SPICE simulations.




(a)




(b)

Fig.4-1 Principles of optical receiver (a) Transimpedance amplifier with feedback resistance (Rs); (b) High impedance amplifier with front-end input load resistance (Rs).

In this chapter, the circuit of fig. 4-2 is designed by the high impedance principle and the circuit of fig. 4-3 is designed by the transimpedance principle. They are discussed and compared in the following paragraphs by considering the important requirements of an optical receiver. The important requirements of an optical receiver are: (1) Receiver sensitivity; (2) bandwidth; (3) dynamic range, and (4) stability. There are other requirements such as high gain, simplicity of circuit, versatility of data rate, power supply constraint, size, cost, etc.

For different optical fiber systems applications, the receiver has different characteristics. For example, the telecommunications systems will require the best sensitivity together with wide dynamic range. On the other hand, the simplicity of circuit and versatility of data rate are more important than optical sensitivity for data link applications which are widely used in computer and switch control networks [8].

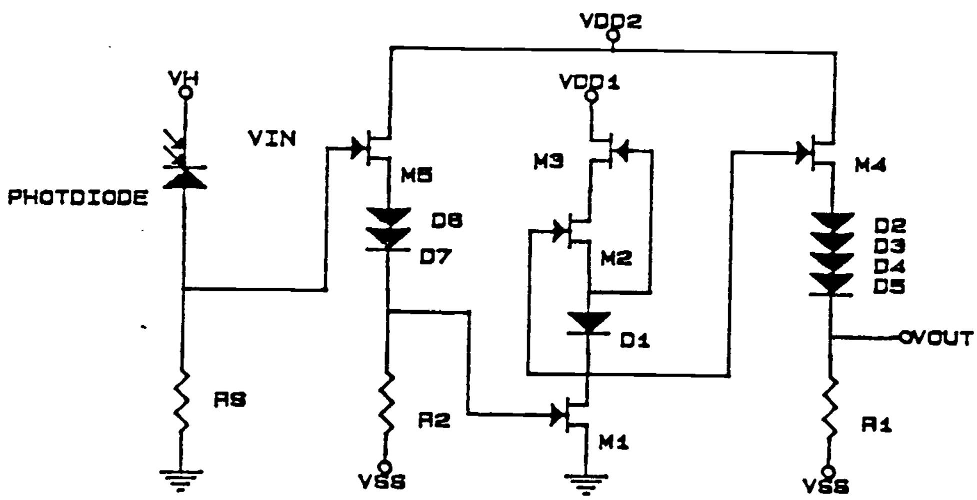



Fig. 4-2 The high impedance amplifier with a front-end input load resistance.

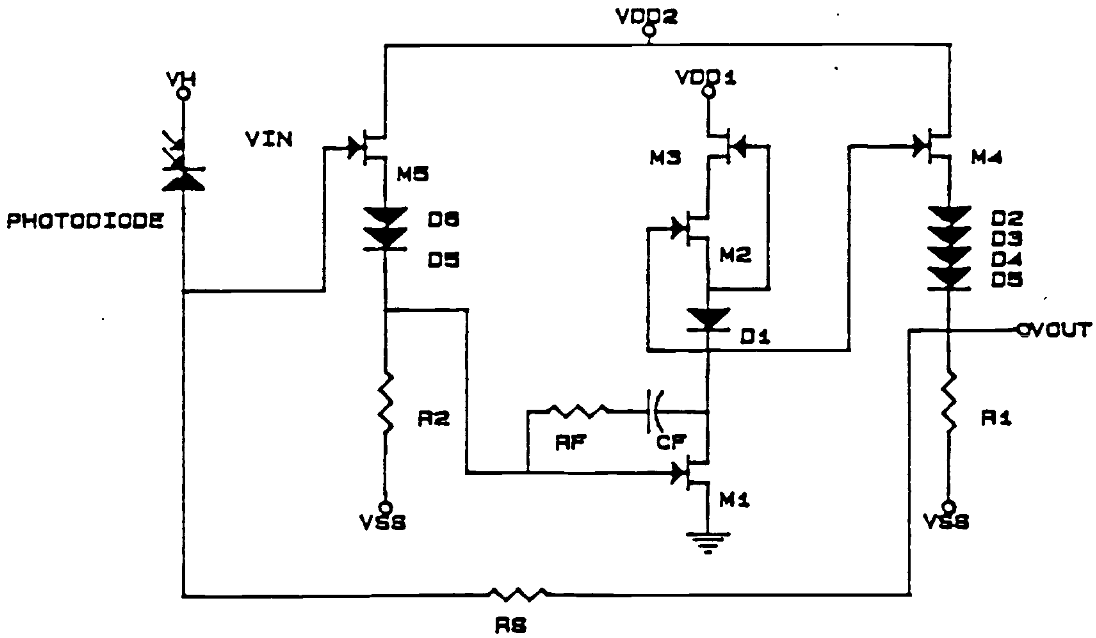



Fig. 4-3 The transimpedance amplifier with a feedback resistance (Rs), a compensation resistance (Rf), and capacitance (Cf).

## 4.1. Receiver sensitivity

The receiver sensitivity is a measure of the minimum optical power level required at the receiver input so that it will operate with a bit error rate less than a desired value. A high receiver sensitivity is essential to achieve the maximun repeater spacing. In both principles (HZ and TZ), a large resistance (Rs) value is required to minimize the noise level and thus maximize the receiver sensitivity. However, high resistance values are not easily compatable with GaAs integrated technology because the sheet resistances of GaAs rarely exceed 500 $\Omega/\square$.

The thermal noise from Rs in the two circuits dominates the receiver sensitivity at high frequencies. The different noise levels with different Rs values are shown in fig. 4-4. Two circuits with the same Rs value and input current source have the same input equivalent noise current (Thermal noise).

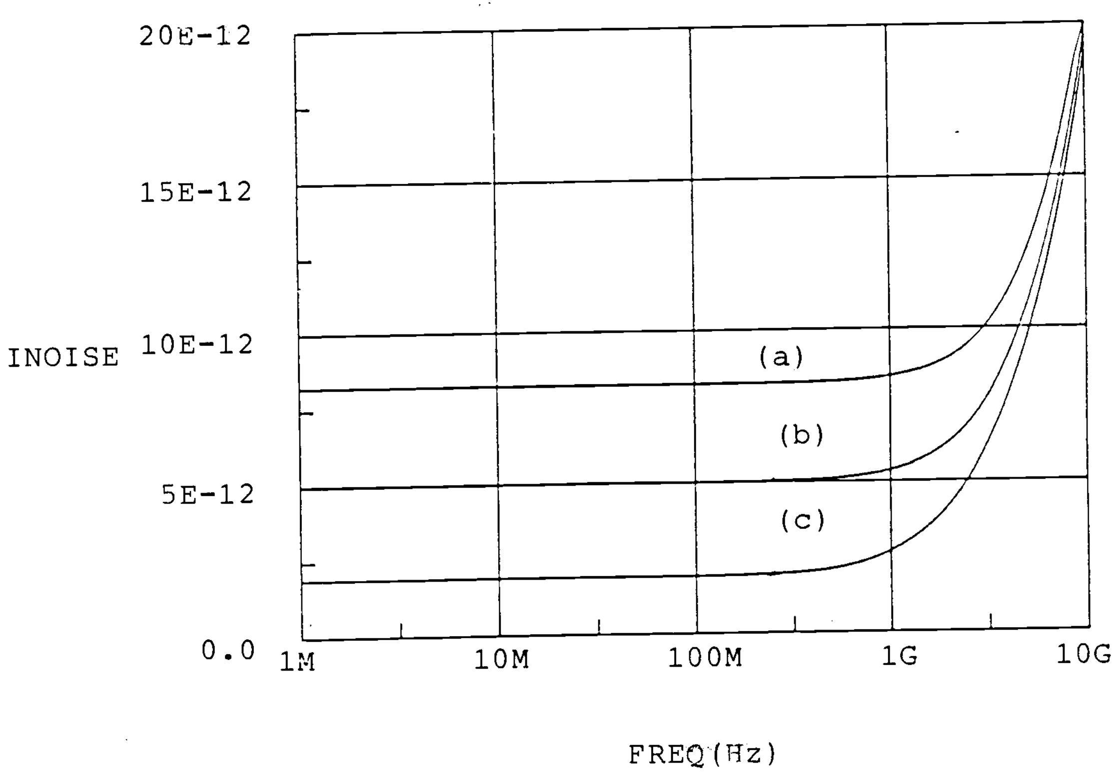



Fig. 4-4 The input equivalent thermal noise current of TZ and HZ amplifier with (a) Rs=500 Ω; (b) Rs=1 kΩ, and (c) Rs=5 kΩ.

## 4.2. Speed

A wide bandwidth is important for high speed optical receivers in a data communication system. The bandwidth of the high impedance receiver amplifier is limited by the RC time constant because of the high load impedance at the front end. Therefore, an equalizer following the amplifier is necessary to extend the bandwidth, but it increases the complexity the of circuit. In fig. 4-5, the larger Rs value the circuit uses, the smaller corner frequency it exhibits.

For the transimpedance amplifier, it is designed to take advantage of the negative feedback effect so that the amplifier bandwidth is extended. Thus no equalizer is required. In fig. 4-6, a 1.4 GHz bandwidth is obtained by using a 5 kΩ feedback reisitor and using an appropriate compensation resistance (Rf) and capacitance (Cf). The bandwidth is larger than the 0.35 GHz bandwidth by using HZ amplfier with 5kΩ Rs.

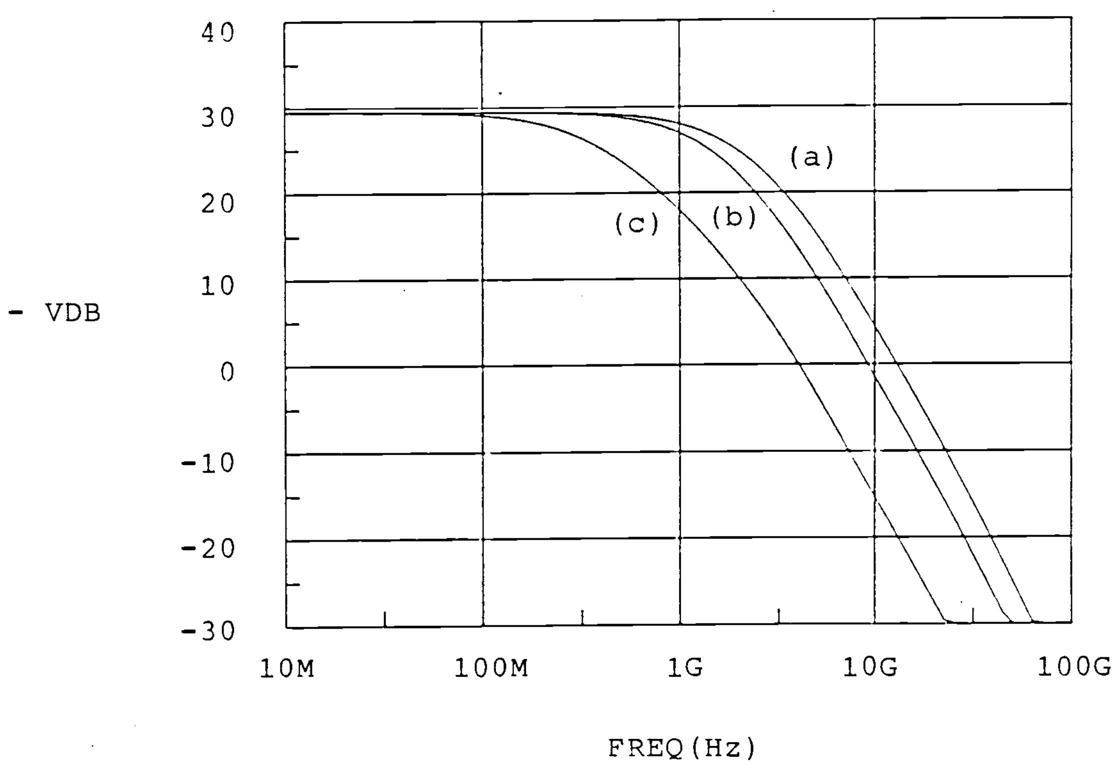



Fig. 4-5 The frequency response of HZ amplifier

(a) Rs=500 Ω; (b) Rs=1 kΩ, and (c) Rs=5 KΩ.

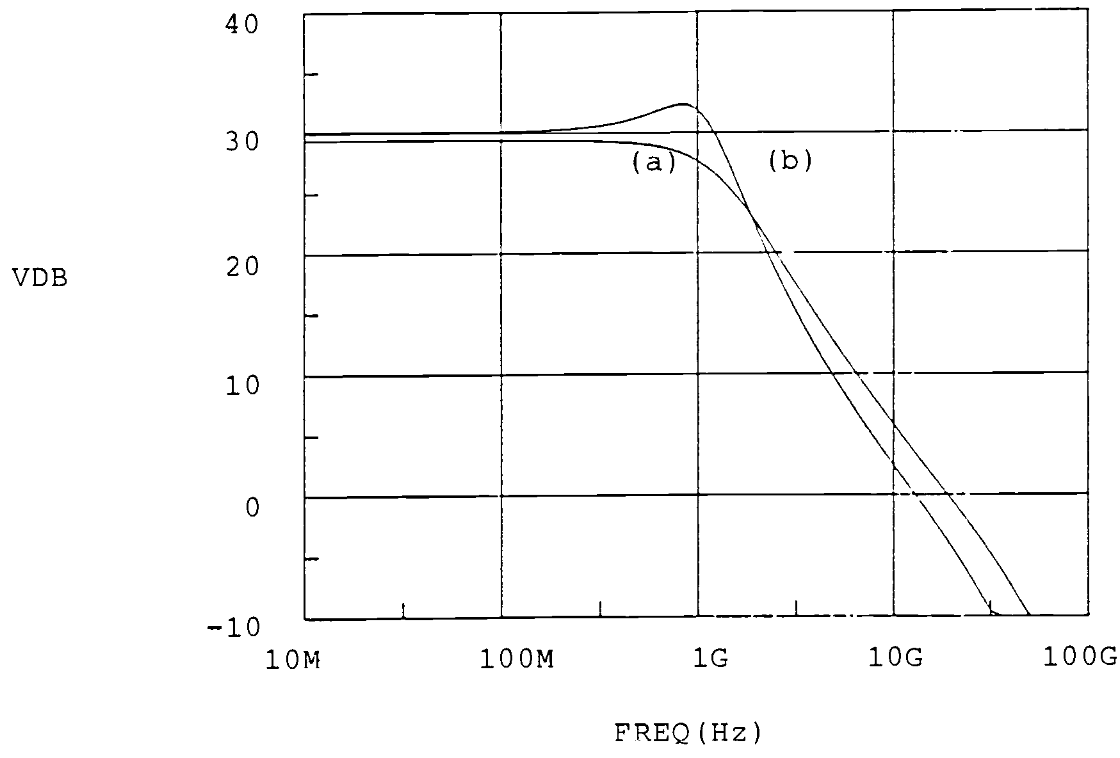



Fig.4-6 The frequency reponse of TZ amplifier with

(a) Rs= 1kΩ, Rf=350 Ω, Cf=0.35 PF, and

(b) Rs= 3kΩ, Rf=450 Ω, Cf=0.18 PF.

## 4.3. Dynamic range

The receiver dynamic range is the difference between the maximun allowable input power level and the minimun detectable power level which is determined by receiver sensitivity. It is a function of Rs (front-end load resistance or feedback resistance) of the receiver amplifier. As Rs decreases, the maximum optical power increases. Thus, the dynamic range increases. However, as Rs decreases, the noise level increases. There is a trade off between high receiver sensitivity and wide dynamic range.

The drawback of high impedance design is the limitation of dynamic range which is due to the high input load impedance. For the transimpedance design, a popular approach is to have the better dynamic range. As can be observed from fig. 4-7 for the HZ amplifier, the input current range is much smaller than for the TZ amplifier.

## 4.4. Stability

Since the high impedance amplifier is a one stage amplifier, stability is not a problem in this ciruit. For the transimpedance amplifier, the feedback resistor is applied over the amplifier. In order to enhance the receiver sensitivity, the feedback resistance is as large as possible

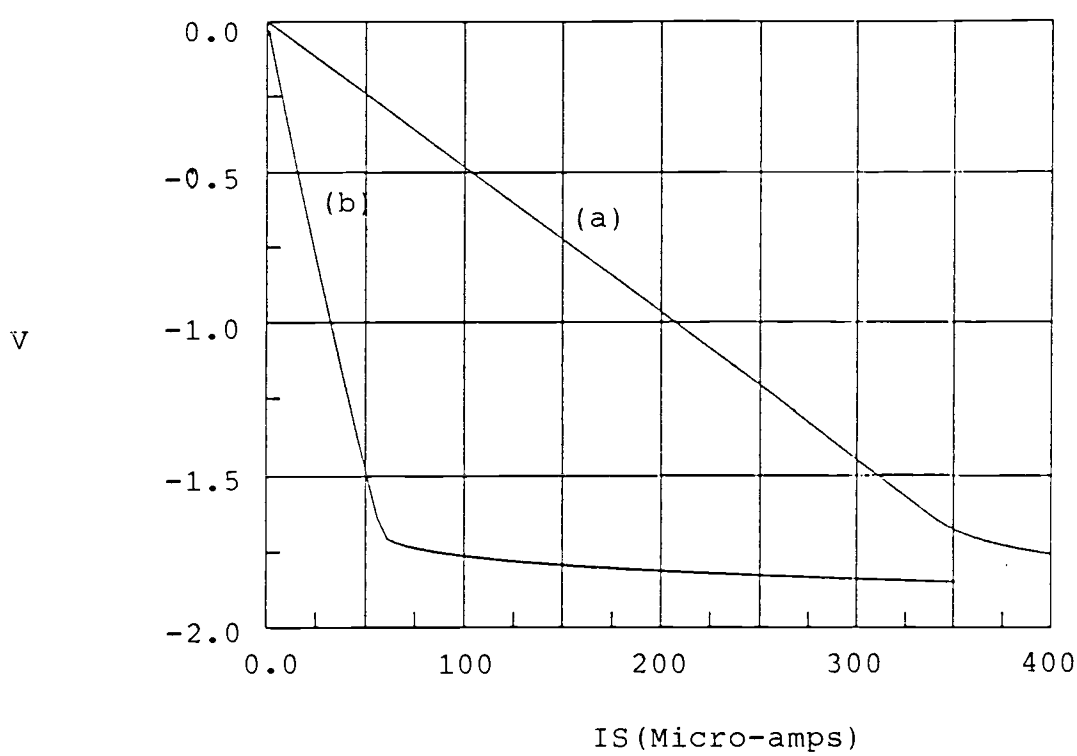



Fig. 4-7 The input current range of (a) TZ amplifier with 5 kΩ feedback resistance, and (b) the HZ with 1 kΩ front-end input load resistance.

It can be increased by increasing the amplifier open-loop gain for a desired bandwidth value. However, the maximun open-loop gain is limited by propagation delay and phase shift of the amplifier stage inside the feedback loop.

In the transimpedance amplifier, a higher gain and adequate phase margin assuring stability are obtained by a feedback resistor (Rs), a compensation resistor (Rf) and capacitor ( Cf). In fig. 4-8, a 57° phase margin is obtained by using a 450 Ω compensation resistance and 0.18 PF compensation capacitance for 3 kΩ transimpedance amplifier.

Besides the above description and comparision, both of the circuits (TZ and HZ) have the limitation of data rate range because the GaAs MESFETs have a high 1/f noise corner frequency (20 - 50 MHz). Therefore, these ciruits are not used in the low bit rate range.

For meeting the requirements of an optical receiver, a 1 kΩ front end input load resistance and a 3 kΩ feedback resistance are used in the HZ amplifier and TZ amplfier, respectively. For both amplifiers, a 0.1 PF detector capacitance and a 1 kΩ load resistance are used in the simulations. The performances of both circuits are listed in Table I.

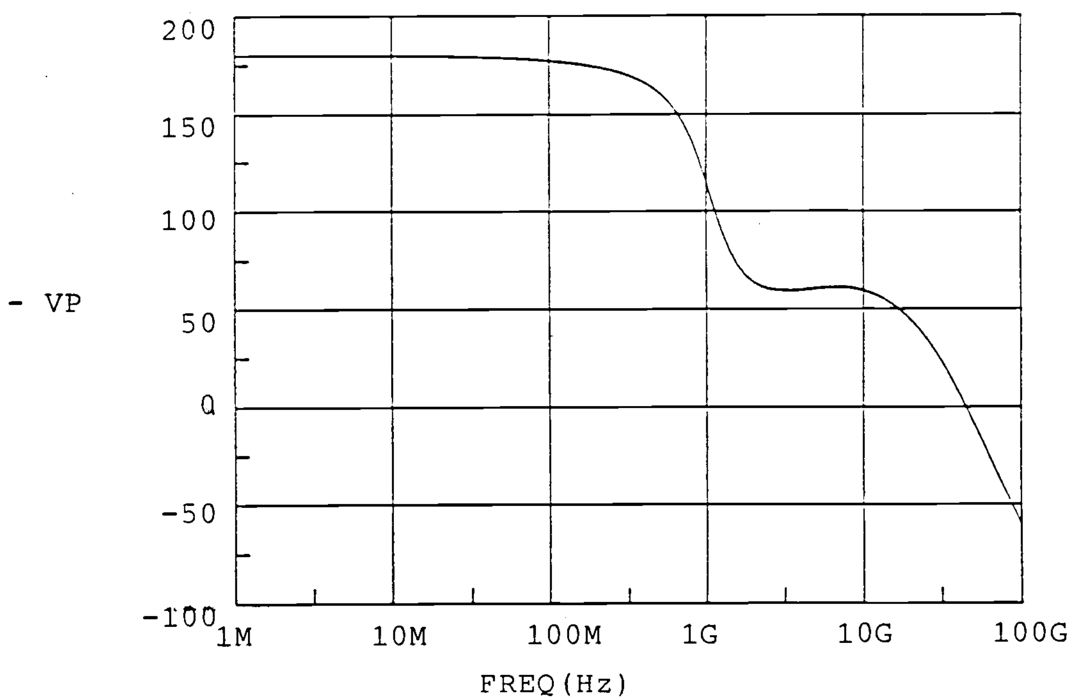



Fig. 4-8 Phase to frequency of the 3 kΩ TZ amplifier with a 450 Ω Rf and a 0.18 PF Cf.

| | TZ AMPLIFIER | HZ AMPLIFIER |
|---|---|---|
| RS | 3 KΩ | 1 KΩ |
| GAIN | 29.3 dB | 29.5 dB |
| BANDWIDTH | 1.5 GHz | 1.1 GHz |
| NOISE LEVEL | 2.55 PA/√Hz | 5.03 PA/√Hz |
| TRANSIMPEDANCE | 2.90 KΩ | 29.6 KΩ |
| PHASE MARGIN | 57° | 30° |
| POWER DISSIP. | 191 mw | 191 mw |
| MAX. IS | 600 μA | 60 μA |

TABLE I. Summary of the results of SPICE simulation for TZ amplifier and HZ amplifier.

# V. CIRCUIT ANALYSIS

The theoretical analysis of optical receivers has been reported in various papers [17]-[20]. In this chapter , the HZ and TZ circuits which were described in previous chapters are analyzed. The gain, transimpedence, cutoff frequency and thermal noise are calculated and compared with the results from SPICE simulation.

## 5.1 Gain

In the main amplifier, the output resistance of the improved "Self-bootstrapped" circuit, ro, is found as [4]

$$ro = [\ 1 + (gm3+gds2)/gds3 + (gm2+gds2)/gD + (gm2+gm3)/(gds3*gD)\ ] \ /\ gds2 \qquad (5\text{-}1)$$

where gD is the cunductance of the diode. According to the MESFET gate widths of the circuit, gD and gm are far greater than gds. Therefore, the output resistance, ro, is simplified as

$$ro \approx (2/gds2) * (1+gm3/gds3) \qquad (5\text{-}2)$$

The gain of the main amplifier GM, is

$$GM = gm1/gout = gm1/(gds1+go), \qquad go = 1/ro$$

$$\approx gm1 \ /\ [\ gds1 + (gds2/2)/(1+gm3/gds3) \qquad (5\text{-}3)$$

From the SPICE simulation:

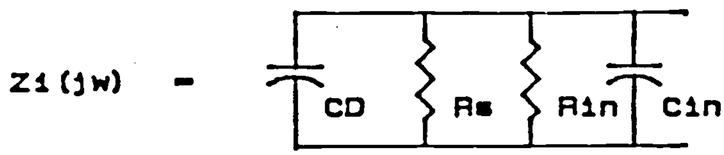
The gain of main amplifier, GM = 44.7

The gain of the input stage = .89

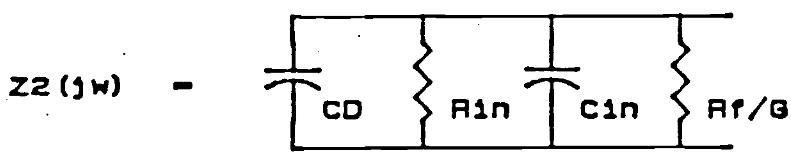
The gain of the output stage = .80

The overall gain of the Hz amplifier, G = 30

5.2. Transimpedence




(a)




(b)

Fig. 5-1 The equivalent circuit of the effective input impedance in (a) HZ amplifier, and (b) TZ amplifier.

In the Hz amplifier approach, the circuit transfer function is

$$H1(jw) = Vout / Iin = G*Z = G*( 1/RT + jwCT )^{-1} \quad (5-4)$$

Z1 is the total effective impedance of the input, RT is the parallel combination resistance of front-end input load resistance (Rs) and input resistance of amplifier (Rin), and CT is the total capacitance of the photodiode (CD) and the input capacitance of the amplifier. The input resistance of amplifier, Rin, is much greater than the front-end input load resistance, Rs. Therefore, the total resistance, RT, is approximately equal to Rs. At the frequency of 100 MHz, the magnitude of input effective impedance , |Z1|, is

$$|Z1| = \sqrt{(1/RT)^2 + (wCT)^2} \approx Rs \quad (5-5)$$

$$|H1(jw)| = G*|Z1| = G*Rs = 30\ k\Omega \quad (5-6)$$

In the TZ amplifier approach, the circuit transfer function is

$$H2(jw) = G*Z2 = G*( 1/Rin + G/Rf + jwCT)^{-1}$$

$$\approx Rf / ( 1 + jwCT/G ) \quad (5-7)$$

At the frequency of 100 MHz, the magnitude of H2(jw) is approximately:

$$|H2(jw)| \approx Rf = 3\ k\Omega \quad (5-8)$$

From the SPICE simulation, the transimpedance of HZ and TZ amplifiers are 29.6 kΩ and 2.9 kΩ at 100 MHz, respectively.

## 5.3 Cutoff frequency

The cutoff frequencies of the HZ amplifier and the TZ amplifier are

$$fc\ (HZ) \approx (CT*G*Rs)^{-1} \tag{5-9}$$

$$fc\ (TZ) \approx (CT*Rf)^{-1} \tag{5-10}$$

If Rs is equal to Rf, the cutoff frequency for the transimpedance amplifier is G times larger than that of the HZ amplifier. From the simulation, the 3-dB bandwidth of the HZ amplifier with a 1 kΩ Rs is 1.1 GHz and the 3-dB bandwidth of the TZ amplifier with a 3 KΩ Rf is extended to 8 GHz. However, a compensation resistance and capacitance are used to enhance the stability. Thus, the compensation reduces the bandwidth of the TZ amplifier with compensation elements (Rf=450 Ω and Cf=0.18 PF) is 1.5 GHz.

## 5.4 Thermal noise

In a resistor R, the thermal current noise is

$$\bar{i}^2 = (4KT\Delta f)/R$$

$$\sqrt{(\bar{i}^2/\Delta f)} = \sqrt{4KT/R}$$

$$\approx 4.07\ \mathrm{PA}/\sqrt{\mathrm{Hz}},\ \text{for 1 k}\Omega\text{ Rs in HZ amplifier}$$

$$\approx 2.35\ \mathrm{PA}/\sqrt{\mathrm{Hz}},\ \text{for 3 k}\Omega\text{ Rs in TZ amplifier}$$

From the SPICE simulation, the thermal current noise of the HZ and TZ amplifiers are 5.03 and 2.55 PA/$\sqrt{\mathrm{Hz}}$, respectively.

# VI. CONCLUSION

The complete circuit consisting of the integrated receiver amplifier together with the SI-GaAs schottky contact photodiode are presented. All GaAs MESFETs devices in the amplifier have a 1 um gate length and a 3 um channel length. The schottky contact photodetector which has a interdigitated structure with 2 um lines and 5 um spacings. is used for doing the SPICE simulation. A 0.1 PF capacitance represents the capacitance of the photodetector and a 1 kΩ load resistance is used in the simulations.

In this thesis, design tradoffs between the conflicting requirements of optical receiver, namely, high receiver sensitivity, wide bandwidth, wide dynamic range etc., are considered. Using a one-micron recessed-gate depletion-mode GaAs MESFET technology, the TZ amplifier characteristics are 29.3 dB gain, 1.5 GHz bandwidth, and 2.55 $pA/\sqrt{Hz}$ input equivalent thermal noise current with a 3 kΩ transimpedance. Moreover, the characteristics of the high impedance amplifier with a 1 kΩ front-end input load resistance are a 29.5 dB gain, 1.1 GHz bandwidth, and 5.03 $pA/\sqrt{Hz}$ input equivalent thermal noise current at 100 MHz.

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