application note

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AN-S011:
Using Silicon MMIC Gain Blocks as Transimpedance Amplifiers

INTRODUCTION

A *transimpedance* (TZ) *amplifier* is a circuit that converts an input current into an output voltage. One very common use of such a circuit is in the receiving end of a fiber–optic system, where the output current from a photodiode must be translated into a usable electrical signal.

The best performing transimpedance amplifiers will be circuits specifically designed to function as such. It is also possible, however, to use low cost general purpose gain block amplifiers as transimpedance amplifiers, especially in systems where state–of–the–art performance is not required. This applications note provides some projections for the use of gain block amplifiers as transimpedance amplifiers in digital fiber–optic systems.

Although this note specifically addresses the use of silicon Microwave Monolithic Integrated Circuits (MMICs) as transimpedance amplifiers, the background theory presented is general in nature and applies equally well to other technologies (e.g. GaAs FET based designs, hybrid gain block amplifiers, etc).

TRANSIMPEDANCE AMPLIFIER PERFORMANCE

Important features of a transimpedance amplifier include the bandwidth (which determines the maximum data rate), the transimpedance gain A_Z, and the equivalent input noise current. These parameters are discussed in some detail below.

Data Rate

The highest data rate at which a gain block can be used as a transimpedance amplifier can be derived from the 3 dB bandwidth it exhibits when used as a conventional amplifier. A wider bandwidth as a gain block equates to higher data rate capability as a transimpedance amplifier. Multiplying the 3 dB bandwidth of an amplifier by 1.5 gives a reasonable estimate of the maximum usable data rate. Commercially available Si MMIC gain blocks are most appropriate for use as TZ amplifiers at data rates up to 800 Mb/s (e.g. for 155 Mb/s or 622 Mb/s systems).

Transimpedance Gain

Transimpedance gain is a measure of the change in output voltage due to a change in input current; as such it has units of volts per ampere, or ohms. It can be calculated from the S parameters using the relationship

$$A_Z = \frac{S_{21}\, Z_o}{(1 - S_{11})} \qquad (1)$$

where S_{21} = the forward gain
S_{11} = input reflection coefficient
Z_o = load impedance.

Note that S_{21} and S_{11} are both vector quantities. The transimpedance gain expressed in decibels can be derived from A_Z in ohms by using the following equation:

$$A_Z\ (\text{dB with respect to } 1\ \Omega) = 20 \log_{10} \{(A_Z \text{ in ohms})/1\ \Omega\} \qquad (2)$$

Example:

Let $S_{21} = 45 \angle 0°$, $S_{11} = 0.1 \angle 0°$, and $Z_O = 50\ \Omega$.

Then

$$A_Z = \frac{(45 \angle 0°)\ 50\ \Omega}{1 - (0.1 \angle 0°)} = 2500\ \Omega$$

and

$$A_Z\ (\text{in dB}) = 20 \log_{10} (2500) = 67.96\ \text{dB}$$

Equivalent Input Noise Current

The equivalent input noise current of a transimpedance amplifier is derived from the noise power encountered in a given bandwidth. Noise power consists of two components: an equivalent input noise current I_n and an equivalent input noise voltage V_n. Since ideally, a TZ amplifier is driven from a current source, no voltage can appear across the amplifier input. Consequently only I_n contributes to the noise performance of a TZ amplifier.

I_n determines the minimum usable signal that can be processed by the TZ amplifier, and as such is analogous to the noise figure F of a conventional amplifier. Unfortunately, there is no simple method available to derive I_n directly from F. Determinations of the equivalent input noise current usually come from direct measurements of product. It is true, however, that a lower noise figure as a gain block will in general result in lower equivalent input noise current as a transimpedance amplifier. Commercially available gain blocks tend to have equivalent input noise currents between 5 pA/√Hz and 20 pA/√Hz.

RECEIVER PERFORMANCE

The sensitivity and the dynamic range of a fiber–optic receiver are significantly influenced by the performance of the transimpedance amplifier used. A discussion of these two parameters follows.

Sensitivity

The sensitivity of a fiber–optic receiver is commonly defined to be the average optical power required to achieve a Bit Error Rate (BER) of 1×10^{-9}. Sensitivity is a function of the optical wavelength of the light source, the quantum efficiency of the detector, and the equivalent input noise current of the TZ amplifier over a given bandwidth.

If some simplifying assumptions are made (most notably that the equivalent input noise current has a flat distribution versus frequency), it is possible to approximate the sensitivity $\bar{p}$ using Equation 3:

$$\bar{p} = \frac{6\, h\, c}{n\, \lambda\, q}\, \bar{i}_n \qquad (3)$$

where h = Planck's constant = 6.63×10^{-34} W s^2
c = speed of light = 3.00×10^{8} m/s
q = electron charge = 1.60×10^{-19} A s
λ = laser wavelength (in meters)

group delay difference leads to more "closed" eye diagram, and hence limits a device to use at lower data rates.

Phase margin (Φ_{PM}) gives an estimate of stability. Devices with a low phase margin are more prone to oscillate. A good rule of thumb is that special care needs to be taken to avoid oscillations when working with devices with phase margins that are less than 60°.

The photodiode capacitance (C_{pd}) is the assumed value of the photodiode impedance for the performance quoted; note that this impedance is further assumed to be purely reactive. Performance will vary with photodiode impedance.

The data labeled I_{MAX} in gives an alternate view of dynamic range; note that not all devices have input current ranges that are symmetrical around 0 µA.

The column labeled "transient" lists a data rate at which the transient response of the transimpedance amplifier is known to be satisfactory.

TABLE 1

Performance of Avantek Si MMIC Gain Blocks as Transimpedance Amplifiers

Die	MSA-06	MSA-07	MSA-08	INA-02	INA-03	ITA-06[1]	ITA-12[1]
BIAS[2]							
Supply	+5V	+5V	36mA	35mA	+5V	+5V	+5V
R_{CC},Ω	100	50	N/A	N/A	200	N/A	N/A
ELECTRICAL PERFORMANCE[3]							
A_Z,dB	54	45	73	65	56	69	72
BW,GHz	0.93	1.34	0.18	0.6	2.5	1.3	0.7
I_n,pA/$\sqrt{Hz}$	10	13	7	7	5	3.5	2.6
V_n,nV/$\sqrt{Hz}$	2.6	0.8	—	—	—	1.5	2.4
$\varnothing_{GD}$,ps	200-300	180-190	1000-500	420-260	190-280	300-500	540-580
Φ_{PM},°	90	90	164	145	20	75	105
C_{pd},pf	1	1	1	1	1	varies	varies
I_{MAX}in,µA	>±1000	>±1000	+1400-800	+600-1000	—	+450	+450
Transient, Gb/s	0.5	1	0.2	0.8	2.5	2.5	1.0
Overall	noisy	noisy	2X FDDI	SONET 622 Mb/s	poor Φ_{PM}	SONET 1.2 Gb/s	SONET 622 Mb/s

Notes.

1. Description of an applications specific designed transimpedance amplifier.
2. Supply: required DC power source
   R_{CC}: Collector bias resistor for operation from specified supply
3. A_Z : Transimpedance Gain
   BW : Bandwidth
   I_n : Equivalent Input Noise Current
   V_n : Equivalent Input Noise Voltage
   $\varnothing_{GD}$: Group Delay
   Φ_{PM} : Phase Margin
   C_{pd} : Assumed source impedance for listed performance (photodiode capacitance)
   I_{MAX}in : Range of DC Input Current over which performance remains linear
   Transient : Satisfactory transient response obtainable to at least this data rate
   N/A : Not applicable
   — : Value not available

$\underline{n}$ = photodiode quantum efficiency (in ratio)
$\bar{i}_n$ = equivalent input noise current x $\sqrt{\text{noise bandwidth}}$ (in A_{rms})

The noise bandwidth of a TZ amplifier will be strongly influenced by the filtering effects of the circuit topology employed in the amplifier design. In general the noise bandwidth will be equal to one half the bit rate times a constant depending on the receiver bandwidth. For a circuit with single pole response, this number is 1.57; for a two pole response it reduces to 1.11. Using the arithmetic mean of these two values (1.34) as a reasonable estimate of the effects of noise filtering results in the approximation that the bit rate is 1.5 times the noise bandwidth. Note that from the approximation used to relate data rate and bandwidth, this value for noise bandwidth is the same as the RF bandwidth of the amplifier.

Example:

Consider a system operating at 622 Mb/s, using a laser with an optical wavelength of 1300 nm and a photodiode with a quantum efficiency of 80%. If the TZ amplifier has an equivalent input noise current of 7 pA/√Hz, then

$$\bar{i}_n = (7\ \text{pA}/\sqrt{\text{Hz}})(622/1.5\ \text{MHz})^{1/2}$$
$$= 143\ \text{nA}$$

and

$$\bar{p} = \frac{(6)(6.62 \times 10^{-34}\ \text{W sec}^2)(3 \times 10^8\ \text{m/s})}{(.8)(1.3 \times 10^{-6}\ \text{m})(1.602 \times 10^{-19}\ \text{A s})}\ 1.43 \times 10^{-7}\ \text{A}$$
$$= 1.02 \times 10^{-6}\ \text{W} = 1.02\ \mu\text{W} = -29.9\ \text{dBm}$$

Dynamic Range

A fiber–optic receiver will have both a minimum optical input power $P_{in\ opt\ min}$ below which it cannot detect signals and a maximum optical input power $P_{in\ opt\ max}$ above which the output of the receiver will have unacceptable levels of distortion. The dynamic range of a fiber–optic receiver in decibels is defined to be the difference between $P_{in\ opt\ max}$ and $P_{in\ opt\ min}$, with both power levels being expressed in dBm. Since the TZ amplifier is the "front end" of the fiber–optic receiver, its performance characteristics will be a primary determiner of both of these power levels.

The $P_{in\ opt\ max}$ of a gain block used as a transimpedance amplifier can be approximated as follows. Start with the output power at 1 dB compression (P_{1dB}) of the gain block, in watts. P_{1dB} provides a conservative estimate of the maximum output power level at which the gain block will have adequate linearity for the desired system performance. For a 50 Ω output system, P_{1dB} can be converted to an output rms voltage using the relationship $V_{out\ rms} = \sqrt{(P_{1dB}\ [\text{Watts}] \times 50\ \Omega)}$. Dividing this voltage by the transimpedance gain A_Z yields the maximum rms input current. Dividing this current by the responsivity r of the photodiode yields the maximum optical input power to the TZ amplifier. r has units of amperes per watt, and can be found on the data sheet of the photodiode. Combining all these relationships results in the following equation for $P_{in\ opt\ max}$. An additional factor of 2 must be introduced to account for input current from a photo diode never being negative.

$$P_{in\ opt\ max} = \frac{\sqrt{(P_{1dB}\ \text{W} \quad 50\ \Omega)}}{A_Z \quad r\ 2} \qquad (4)$$

The minimum optical input power is given by the sensitivity $\bar{p}$, or

$$P_{in\ opt\ min} = \bar{p} \qquad (5)$$

Therefore, the dynamic range in dB is given by

$$\text{D.R.} = 10 \log_{10} \left(\frac{\sqrt{(P_{1dB}\ \text{W} \quad 50\ \Omega)}}{2\ A_Z \quad r \quad \bar{p}} \right) \qquad (6)$$

Example:

Consider the receiver described in the sensitivity example, above. Let the P_{1dB} = +11 dBm, A_Z = 2500 Ω, and R = 0.8 A/W. Then

$$\text{D.R.} = 10 \log_{10} \left(\frac{\sqrt{(.012\ \text{W} \quad 50\ \Omega)}}{2 \times 2500\ \Omega \quad 0.8\ \text{A/W} \quad 1.02 \times 10^{-6}\ \text{W}} \right)$$
$$= 10 \log_{10} (.7746/.00408)$$
$$= 22.8\ \text{dB}$$

CIRCUITRY

The following paragraphs explain how to change a conventional microwave amplifier circuit using a MMIC gain block into a transimpedance amplifier circuit.

The TZ amplifier will have as a drive signal the current from a photodiode, so any conventional amplifier input circuitry is removed and the output of the photodiode is connected directly to the input of the gain block. No blocking capacitor is required between the photodiode and the gain block. Since photodiode capacitance in addition to any stray capacitance can have a significant effect on the noise performance and bandwidth of an optical receiver, the distance between the photodiode and the TZ amplifier should be minimized. For this reason it is sometimes desirable to use unpackaged MMIC chips for transimpedance amplifier applications. In this configuration the output of the photodiode is wire bonded directly to the input of the gain block.

The output of the TZ amplifier usually drives a limiting or AGC amplifier before regeneration and possible de–multiplexing. Thus the RF output circuit for the TZ amplifier is typically a 50Ω transmission line, just as it is for a conventional amplifier. The output circuit will require either a DC blocking capacitor or level shifting so that the power supply voltage applied to the TZ amplifier does not effect the DC level on the input of the following stage.

Both conventional amplifier and TZ amplifier circuits use the same DC bias circuitry.

PERFORMANCE DATA

The table below characterizes a number of Hewlett-Packard Si MMIC gain blocks as transimpedance amplifiers. Included are devices from both the MODAMP™ MMIC family and the magIC™ INA family. Since many of these products are available in more than one package option, the performance is listed by die type, not part number. Preliminary data sheets characterizing the MSA-0886 and INA-02170 products as a transimpedance amplifiers are available from the Hewlett-Packard factory. Hewlett-Packard also offers silicon MMICs specifically designed to function as TZ amplifiers. The performance of two such die, the ITA-06300, and ITA-12300, are included for comparison in Table 1.

In addition to transimpedance gain, bandwidth, and input equivalent noise current and voltage, a number of other parameters appear in the table.

Group delay ($\varnothing_{GD}$) supplies another way of estimating the appropriate data rates for the gain block as a TZ amp. A large

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