Performance Analysis of Bootstrap Transimpedance Amplifier For Large Windows Optical Wireless Receiver

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Abstract- Due to optical wireless link power budget considerations, the receiver is required to have a large collection area. One of the main noise mechanisms in wideband preamplifiers employing large area detectors is the noise due to the low pass filter formed by the detector capacitance and the input impedance to the preamplifier. Typical large photodetection area commercial detectors has capacitance are around 100-300 pF compared to 50pF in fiber link. Hence, techniques to reduce the effective detector capacitance are required in order to achieve a low noise and wide bandwidth design. In this paper analysis on the bootstrap transimpedance amplifier (BTA) for input capacitance reduction will be reported. This technique offers the usual advantages of the transimpedance amplifier together with an effective capacitance reduction technique for optical wireless detector.

Keyword: Wireless optical communication, Transimpedance amplifier, photodetector, Bootstrap

1. Introduction

Since, the optical wireless link operates with limited transmitter power, due to safety considerations, in relatively high noise environments as a result of ambient light levels. Thus, the performance of the optical receiver has a significant impact on the overall system performance. In order to reduce shot noise in the detector due to ambient light an optical filter is required, whilst the preamplifier should allow shot-noise limited operation.

Due to link budget considerations, the receiver is required to have a large collection area, which may be achieved through the use of an optical concentrator (effectively noiseless gain) [1], a large area photodetector or a combination of the two. Since indoor optical transceivers are intended for mass computer and peripheral markets, the receiver design is extremely cost sensitive, which can make sophisticated optical systems unattractive.

The design of an optical receiver depends on the modulation format used by the transmitter. The optical wireless receiver system are, essentially consists of the photo detector plus a pre-amplifier with possibly additional signal processing circuit. Therefore, it is necessary to consider the properties of this device in the context of the associated circuitry combined in the receiver. It is essential that the detector perform efficiently with the following amplifying and signal processing.

However for all optical receivers, fiber and wireless alike, their sensitivity is a trade off between photodiode parameters and circuit noise. Applications that require a good sensitivity and a broad bandwidth will invariably use a small area photodiode, which means that the aperture is small. Receivers for long distance point-to-point fiber systems generally fall into this category. Conversely, for wireless optic applications require a large aperture and so must use a large area photodiode, where upon sensitivity and speeds are reduced [2]. As expected the sensitivity improves (i.e., reduces in numerical value) as the photodiode area reduces because of the correspondingly lower capacitance. However, small area photodiodes incur a greater coupling loss due to the small aperture they present to the incoming beam, so a careful trade off between these factors is necessary to optimize the overall performance.

Figure 1 shows that a receiver with an APD gives an 10dB sensitivity advantage over a corresponding PIN receiver, which is consistent with

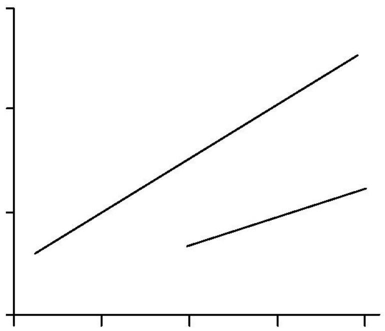

Figure 1: Receiver sensitivity (at 155Mbps) in relation to photodiode type and detection area [2].

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observations on optical fiber receivers. APD receivers however are more costly and require high operating voltages, hence are predominantly used in specialist systems where performance is key. Oppositely, for indoor systems which economy is a priority, favor PIN receivers.

2. Preamplification Technique

The current from the detector is usually converted to a voltage before the signal is amplified. The current to voltage converter is perhaps the most important section of any optical receiver circuit. An improperly designed circuit will often suffer from excessive noise associated with ambient light focused onto the detector. To get the most from the optical signal through the air system, the right front-end circuitry design must be considered. An optical receiver's front-end design can be usually grouped into these pre-amplification techniques: low-impedance voltage amplifier; a high impedance amplifier; and a trans-impedance amplifier. Any of the configurations can be built using contemporary electronics devices i.e. bipolar junction transistors (BJT), field effect transistors (FET), or high electron mobility transistors (CMOS). The receiver performance that is achieved will depend on the devices and design techniques used.

An equivalent circuit of a PN junction photodetector with and input the preamplifier stage is shown in Figure 2. The diode shunt resistance, R_j, in a reverse biased junction is usually very large ($>10^6\Omega$), compared to the load impedance R_l, and can be neglected. The resistance R_s represents ohmic losses in the bulk *p* and *n* regions adjacent to the junction, and C_d represent the dynamic photodiode capacitance.

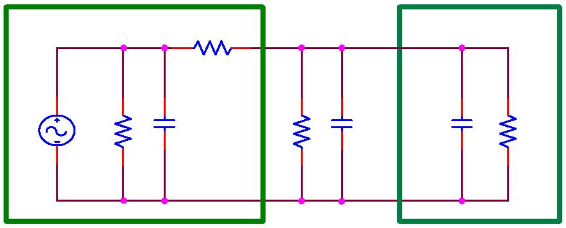

Figure 2: Simple equivalent circuit for PN or PIN photodetector.

The design of the front-end requires a trade-off between speed and sensitivity. Since using a large load resistor RL can increase the input voltage to the preamplifier, high impedance front-end is often used. Furthermore, a large R_L reduces the thermal noise and improves the receiver sensitivity. The main drawback of high impedance frond-end is its low bandwidth given by $\Delta f = (2\pi R_L C_T)^{-1}$, where $Rs \ll R_L$ is assumed and C_T includes the contributions from the photodiode (C_d) and the transistor used for amplification (C_a). A high-impedance front-end cannot be used if Δf is considerably less than the bit rate. An equalizer is sometime used to increase the bandwidth. The equalizer acts as a filter that attenuates low-frequency components of the signal more than the high-frequency components, thereby effectively increase the front-end bandwidth. If the receiver sensitivity is not of concern, one can simply decrease R_L to increase the bandwidth, resulting in a low impedance front-end. Transimpedance front ends provide a configuration that has high sensitivity together with a large bandwidth. Its dynamic range is also improved compared with high-impedance front ends.

Optical fiber receivers mostly employ a transimpedance design because this affords a good compromise between bandwidth and noise, both of which are influenced by the capacitance of the photodiode. However, the large area photodiodes that are essential in optical wireless require designs that are significantly more tolerant of high device capacitances. A design that is will use in optical wireless receivers combines transimpedance with bootstrapping, the latter of which reduces the effective photodiode capacitance as perceived by signals. This allows a relatively high feedback impedance to be used, which reduces noise and increases sensitivity.

3. Bootstraps Transimpedance Amplifier

Due to optical wireless link power budget considerations, the receiver is required to have a large collection area. One of the main noise mechanisms in wideband preamplifiers employing large area detectors is the noise due to the low pass filter formed by the detector capacitance and the input impedance to the preamplifier. Typical large photodetection area commercial detectors has capacitance are around 100-300 pF compared to 50pF in fiber link. Hence, techniques to reduce the effective detector capacitance are required in order to achieve a low noise and wide bandwidth design.

Significantly, in any photodetector application, capacitance is a major factor, which limits response time. Decreasing load resistance improves this aspect, but at the expense of sensitivity. In the subsequent amplifier, positive feedback may be used with caution. It is possible to combine the effective stability of negative feedback with the desirable features of the positive type. Beside that, the input capacitance in effect constitutes part of the feedback network of the op-amp and hence reduces the available loop gain at high frequencies. In some cases a high input capacitance can cause the circuit to have a lightly damped or unstable dynamic response. Lag compensation by simply adding feedback capacitance is generally used to guarantee stability, however this approach does not permit the full gain-bandwidth characteristic of the op-amp to be fully exploited. An alternative approach, the bootstrap transimpedance amplifier (BTA) for input capacitance reduction has been reported by [3, 4] was previously intended for receiver bandwidth enhancement. This technique offers the usual advantages of the transimpedance amplifier together with an effective capacitance reduction technique for optical wireless detector mentioned above.

4. BTA Circuit Design and Simulation

The basic bootstrapping principle is to use an additional buffer amplifier to actively charge and discharge to input capacitance as required. By doing so the effective source capacitance is reduced, enabling the overall bandwidth of the circuit to be increased. There are four possible bootstrap configurations (series or shunt bootstrapping modes, with either floating or grounded sources), both are shown in Figure 2 (a) and (b) respectively, which can be applied to the basic circuit. The series configuration and shunt technique can be found in [5].

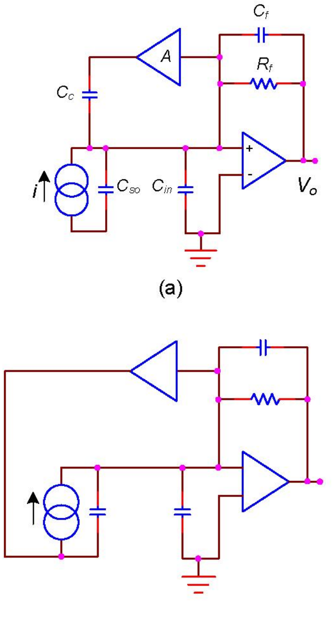

Figure 3: Equivalent circuit for shunt BTA (a) grounded source and (b) floating source.

A much improved version of the circuit, incorporated within a transimpedance amplifier reported in [4] has been use to simulate the BTA bandwidth performance and the effect feedback capacitance to reduce effective photodiode capacitance and. This bootsrap transimpedance amplifier arrangement is consisted of four stages. There is unity gain, FET buffer, cascade amplifier and buffer output. The type of this circuit is Floating Source and Series Bootstrap Transimpedance Amplifier.

In this arrangement, the gain of transistor J1 was found not necessary, as Q1/Q2 provided the diode current. Q_1 itself acted as an emitter follower from the source of J_2 and Q_2 was a current source, driven from the source of J_3. The photodiode capacitance was bootstrapped by the J_1, stage in conjunction with Q1. An FET buffer, J_3, drove a dipolar cascade circuit Q_3/Q_4, buffered by Q_5. Overall feedback was given from the emitter of Q_5 to the gate of J1. Capacitance C_f was used to reduce the effects of stray capacitance of the feedback resistor. R_4 and C_2 were used to bootstrap the input to J_2 to keep its input impedance high [4].

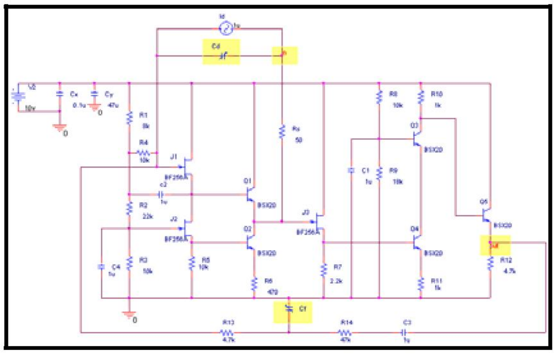

Figure 4: The schematic circuit of Floating Source and Series Bootstrap Transimpedance Amplifier.

The photodiode and detected optical signal was model as a current source in the front-end optical receiver equivalent circuit as shown in Figure 4. The model was simulated using PSPICE, where the positions for each node photodiode and feedback capacitance are highlighted. The photodiode and feedback capacitance are varied to observe the performance characteristics of the BTA. The transistors used in this circuit are BSX 20 – NPN bipolar transistor and BF256A - n-channel JFET depletion.

Since wider photodetection area was needed for optical wireless, that will incorporating larger effective photodiode capacitance as perceived by signals. Therefore, photodiode capacitance C_d with 0.1µF was used in this simulation for variable value of feedback capacitance, C_f. Figure 5 shows the frequency response of the simulated BTA with C_d =

0.1μF and feedback capacitance, C_f = 0F, and peaking gain, M_p is 9.0dB and 3dB bandwidth 1.90GHz were obtained. By varying the C_f with fixed value of C_d, it was shown that the BW decreases and peaking gain were reduce simultaneously. This is shown by Figure 6 the effect the feedback capacitance, which the C_f will improve system stability.

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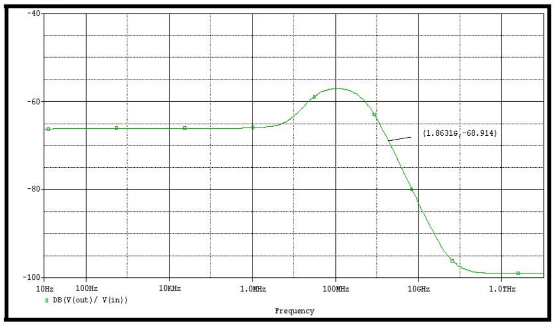

Figure 5: BTA frequency response with feedback capacitance, C_f = 0F and photodiode capacitance, C_d= 0.1μF.

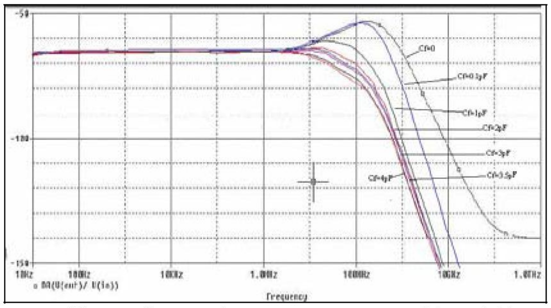

Figure 6: BTA frequency responses with variable feedback capacitance, C_f and photodiode capacitance, C_d= 0.1μF.

By measuring the bandwidth for each value of feedback capacitance, the relationship between the feedback capacitance and the BTA frequency responses can be plotted as shown in Figure 7. Simultaneously, the peaking gain is also changing by varying the feedback capacitance value as shown in Figure 8. Thus in general observation, it was found that the most effective value of feedback capacitance, let say for C_d= 0.1μF will be 3.5pF because there is no peaking gain and the bandwidth considerably high at 33.4 MHz. However, it was shown that the bandwidth improved significantly for lower C_d as shown in Figure 9 for the BTA circuit with C_f=3.5 pF. In order to obtain a critically damped response the shunt circuit required a smaller value of feedback capacitance, indicating that bootstrapping had effectively reduced the source capacitance. The increase in bandwidth can be attributed to the decrease in feedback capacitor required to produce a critically damped response.

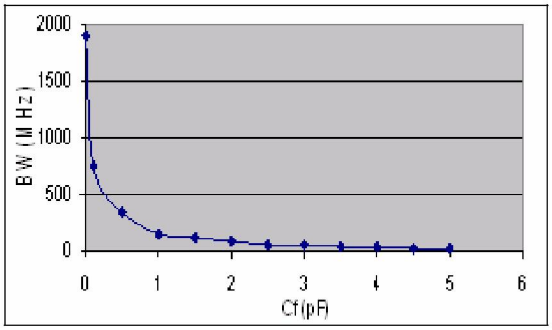

Figure 7: BTA bandwidth decreases with the feedback capacitance.

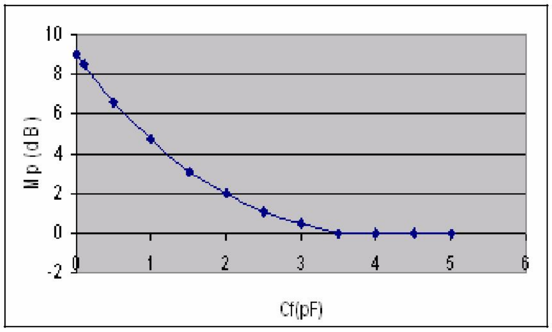

Figure 8: Peaking gain decreased with the feedback capacitance.

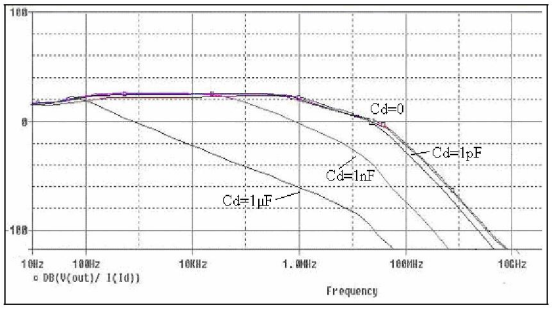

Figure 9: BTA frequency responses with 3.5pF feedback capacitance.

5. Conclusion

In this work various optical front-end receiver design were studied. Receivers for long distance point-to-point fiber systems generally require a good sensitivity and a broad bandwidth will invariably use a small area photodiode. Oppositely, for wireless optic applications require a large aperture and large photodetection area, where upon sensitivity and speeds are reduced. As expected the sensitivity improves as the photodiode area reduces because of the correspondingly lower capacitance. However, small area photodiodes incur a greater coupling loss due to the small aperture they present to the incoming beam. Optical fiber receivers mostly employ a transimpedance design because a good compromise between bandwidth and noise, both of which are influenced by the capacitance of the photodiode. However, the large area photodiodes that are essential in optical wireless require designs that are significantly more tolerant of high device capacitances. Hence, in optical wireless receivers combines transimpedance with bootstrapping, whereby the bootstrapping reduces the effective photodiode capacitance as perceived by signals.

This paper has presented an overview of basic bootstrap configurations for the standard transimpedance amplifier. The circuit was simulated and frequency responses of the floating source and series bootstrap transimpedance amplifier were presented. The design has presented a simple example of a shunt bootstrap amplifier based on two operational amplifiers of the same type and shows that the techniques can be used to realized a faster response than is possible with a single amplifier alone. The bootstrap method may provide a viable design option for applications with high gain and requiring a wide bandwidth.

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