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THE EFFECTS OF A FEEDBACK CAPACITOR IN AN OPTICAL RECEIVER DESIGNED WITH TRANSIMPEDANCE AMPLIFIER

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Abstract. This paper reports the effect of adding a feedback capacitor in the opto-electrical receiver with a transimpedance amplifier (TIA). A TIA is used in a receiver to provide for both high speed and high gain. However, there is a problem faced when developing a receiver with TIA; gain peaking, which creates an unstable output. A simple approach of placing a feedback capacitor on the amplifier was found to reduce the peaking from 2 dB down to 0 dB.

Keywords: Optical, receiver, transimpedance, amplifier, feedback, capacitor, gain, peaking

Abstrak. Kertas teknikal ini melaporkan kesan penambahan satu kapasitor suap balik di dalam penerima opto-elektrik menggunakan penguat transgalangan (TIA). TIA digunakan di dalam penerima untuk menyokong kedua-dua kelajuan dan gandaan tinggi. Walau bagaimanapun, satu masalah yang dihadapi apabila membina penerima dengan TIA iaitu gandaan memuncak menghasilkan output yang tidak stabil. Satu pendekatan mudah iaitu meletakkan satu kapasitor suap balik dalam litar penguat didapati telah mengurangkan puncak tersebut dari 2 dB ke 0 dB.

Kata kunci: Optik, penerima, transgalangan, penguat, suap balik, kapasitor, gandaan, puncak

1.0 INTRODUCTION

Receiver is one of the major elements in communication systems. Its principal function is to receive signals and reconstruct the message as close as possible to the original. Thus good receiver designs are extremely important since a receiver serves as the final piece of communication equipment interfacing with the end user. The amplifier gain, frequency response (bandwidth) and sensitivity are the main parameters specifying a receiver. Optical receivers are generally sub-divided into two parts; front-end and the demodulation blocks. The main components of the front-end block are photodetector and amplifiers. This report focuses on the front-end design only. At the photodetector, the data is received in optical signal and directly converted to its electrical form. Usually, the optical signal converted to the electrical form is weak and measured in microamperes (μA), which is not sufficient for further signal processes like demodulation [1]. In order to increase the magnitude of the electrical signal, amplifier circuit is introduced

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in the optical receiver system. The other function of an amplifier is to act as a current to voltage converter. This conversion is vital for the signal processing which is voltage based, whereas the photodetector is a current mode component [2]. While amplifiers are very important in a receiver design, its inclusion introduces another problem; gain peaking. Gain peaking in the frequency response of the receiver affects in reduction of bandwidth and instability of signal [3].

This paper reports that by a simple use of a feedback capacitor, the gain peaking problem can be minimized. The calculation for the required capacitance was derived and provided. Simulation results obtained showed that a significant gain peaking reduction can be achieved.

2.0 WORKING PRINCIPLE

Basically, transimpedance configuration is a high-gain high impedance amplifier with a feedback provided to the amplifier input through the feedback resistor, R_f. This design gives both low noise and a large dynamic range. The introduction of R_f in the amplifier circuit changes the nature of the amplifier from open loop amplification to closed loop amplification [4]. The new circuit now becomes more complex and involves imaginary variables in its characteristic. This can be shown by its equivalent circuit in Figure 1.

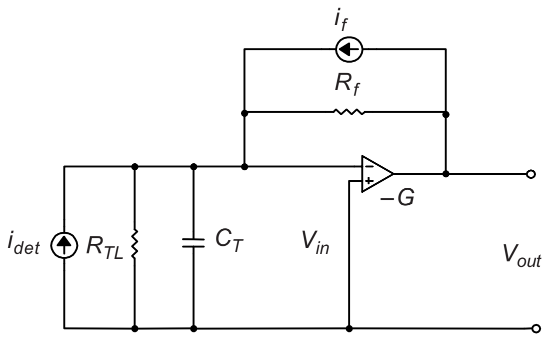

Figure 1 Optical receiver with transimpedance amplifier equivalent circuit

The improvement made to the ordinary circuit is the insertion of a capacitor parallel with the feedback resistor. The capacitance of the transimpedance amplifier (common-mode input capacitance, $C_{in(CM)}$ and differential input capacitance, $C_{in(Diff)}$) and the detector's capacitance, C_D are in parallel. Hence, the total internal capacitance, C_T of the section is equal to $C_{in(CM)} + C_{in(Diff)} + C_D$. This summation has resulted in a higher total capacitance. The parasitic input capacitances are shown in the equivalent circuit of Figure 2 [5].

Due to the detector's capacitance, C_D, the op-amp in Figure 2 behaves as if it is in a differentiator configuration. Differentiator circuit should be avoided in the design

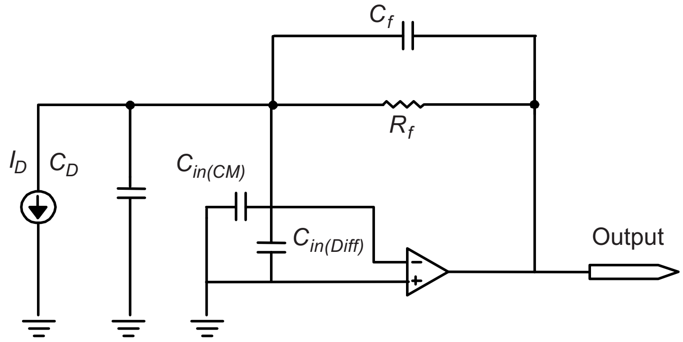

Figure 2 Circuit model for parasitic input capacitances analysis

because it is known as a noise magnifier. This is due to its nature that produces spikes at the output every time there is a sharp change in input [6]. Without the feedback capacitor, C_f, the circuit will oscillate and suffers from the stability problem.

To determine the value of C_f, its Q factor in the circuit was used. Q factor or quality factor of a capacitor is the ratio of a component's reactance to its effective series resistance [7]. For the amplifier circuit, Q factor can also be used in bandwidth calculations. The equation for Q factor was derived originally from Equation (1).

$$H_{CL}(\omega) = \frac{-R_f}{1 + \left(\frac{j\omega C_T R_f}{G}\right)} VA^{-1} \tag{1}$$

This equation is for a low pass first-order transfer function. With the insertion of C_f in the circuit, the function becomes second order transfer function and the equations for Q factor is rewritten and simplified as [3]:

$$Q = \frac{\sqrt{(GBWP)(Z)}}{Z + GBWP \dfrac{C_f}{C_f + C_T}} \tag{2}$$

where the Gain Bandwidth Product ($GBWP$) of the amplifier (in radians) is:

$$\begin{aligned} GBWP &= 2 \text{ GHz} \times 2\pi \\ &= 1.26 \times 10^{10} \end{aligned}$$

and the impedance is:

$$Z = \frac{1}{R_f (C_f + C_T)} \tag{3}$$

It is found that gain peaking occurs as the signal approaches cut off frequency. This peaking region is undesirable as it reduces the cut off frequency. To minimize or possibly eliminate the peaking, the Q value must be less than or equal to 0.707 [6].

Taking $Q \leq 0.707$, $R_f = 1.8\ \text{k}\Omega$, $GBWP = 1.26 \times 10^{10}$ and $C_T = 2.9$ pF, and by using Equation (2), we have:

$$0.707 \geq \frac{\sqrt{1.26 \times 10^{10} Z}}{Z + 1.26 \times 10^{10} \left(\dfrac{C_f}{C_f + 2.9 \times 10^{-12}} \right)}$$

and using Equation (3), we have:

$$Z = \frac{1}{1.8 \times 10^{3} \left(C_f + 2.9 \times 10^{-12} \right)}$$

By combining both equations,

$$\begin{aligned} C_f &\geq 0.5 \times 10^{-12} \\ &\geq 0.5\ \text{pF} \end{aligned}$$

Based on the calculations above, it can be concluded that in order to increase the stability of the receiver and minimize the oscillation and frequency peaking in the circuit, the feedback capacitor, C_f, must be at least 0.5 pF. This parameter is derived when the feedback resistor is set to 1.8 kΩ. Nevertheless, C_f must not exceed the total internal capacitance, C_T, to avoid the reduction in –3 dB frequency.

3.0 SIMULATION

For the purpose of the study, two designs were used; the front-end with a transimpedance amplifier, and the same circuit with an addition of a capacitor in parallel to the feedback resistor. The latter is illustrated in Figure 3.

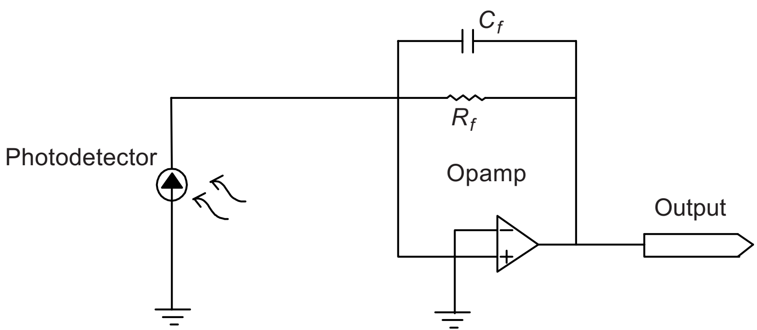

Figure 3 TIA circuit with feedback capacitor

The simulation was carried out using commercial software, Electronic Workbench. Limitation of the simulation is that it has no optical source. Thus, an AC current source was used to simulate the opto-electrically converted current. The electrical noise was also simulated to make the simulation more realistic.

4.0 RESULT AND DISCUSSION

The gain formula for the transimpedance amplifier is $20\log_{10}\frac{V_{rms}}{I}$, where V_{rms} is 0.707 multiplied by a half of its peak-to-peak value measured by the oscilloscope [4]. Meanwhile the bandwidth, B, is in $\log_{10}$ unit where $B = \log_{10} 2\pi f$ and f is the varied input frequency.

Figure 4 is the simulated gain versus bandwidth for optical receiver with transimpedance amplifier. From the graph, it can be seen that the gain of the receiver circuit is constant around 65 dBΩ for a bandwidth around 6 or 200 kHz. After that the gain peaks around 67 dBΩ over a bandwidth of 7 or 10 MHz before decreasing sharply for the bandwidth above 9 or 150 MHz.

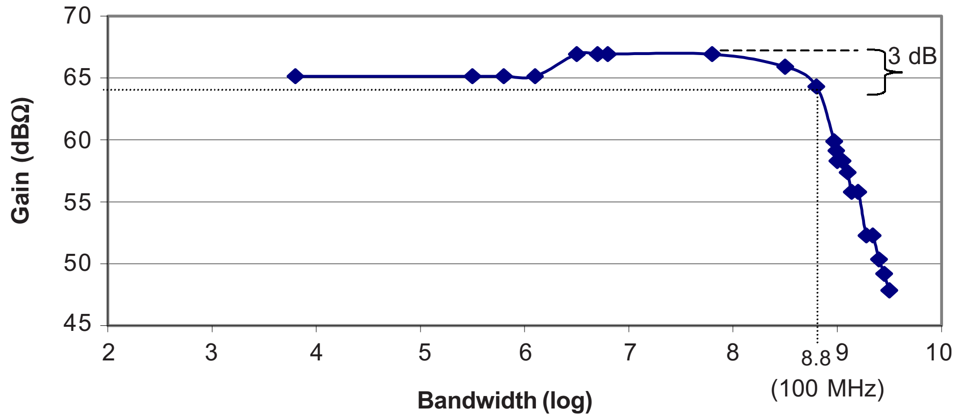

Figure 4 Simulated gain versus bandwidth for optical receiver with transimpedance amplifier

Figure 5 shows the graph of simulated gain versus bandwidth for optical receiver with the feedback capacitor. The simulation was done with the input optical power equals to 0 dBm.

The graph shows that the gain peaking that exists in the previous circuit has been eliminated with the introduction of the feedback capacitor. The gain obtained from the graph is consistent around 65 dBΩ. When approaching the bandwidth around 8.8 or 100 MHz, the gain starts to roll off abruptly. The minimum gain calculated at the highest frequency simulated point around 9.5 or 500 MHz is around 47 dB. The

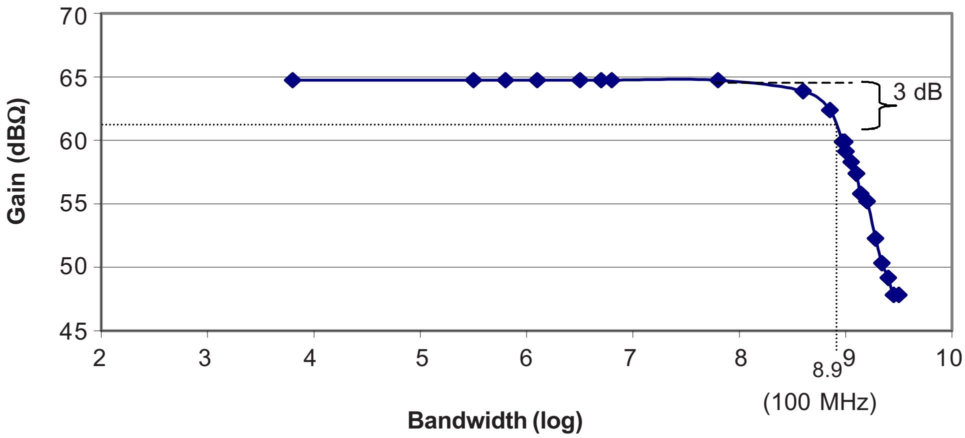

Figure 5 Simulated gain versus bandwidth for optical receiver with feedback capacitor

maximum gain calculated is the same as the initial gain achieved in the optical receiver circuit without the feedback capacitor. This shows that the introduction of the feedback capacitor reduces the gain peaking while maintaining its gain.

Note that the bandwidth scales in Figures 4 and 5 are in logarithmic scale. Hence the 3 dB bandwidth which is 8.8 in Figure 4 and 8.9 in Figure 5 seem to show a little improvement. However, if the values are converted to linear scale, both 8.8 and 8.9 will give 100 and 126 MHz respectively. An increase of 26 MHz can be considered as a substantial improvement in 3 dB bandwidth made by the insertion of the feedback capacitor.

5.0 CONCLUSION

From this study, it is shown that the introduction of the feedback capacitor, C_f, has significantly reduced the peaking problem and maintained the gain. In the study, C_f must be at least 0.5 pF for the receiver using TIA with 2 GHz gain bandwidth product. The new design has reduced the peaking problem from 2 dB down to 0 dB. The elimination of the peak is very significant to give a better optical receiver performance by increasing its 3 dB bandwidth.

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