Noise Analysis of a Millimeter-Wave Photoreceiver and Noise Performance Improvement

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Abstract – A noise analysis of a 30GHz photodiode plus matched amplifier photoreceiver is presented and a method for noise performance improvement described. It is shown that a 12.4 dB improvement in optical sensitivity can be achieved.

1. Introduction

The photoreceiver analysed in this paper was designed at the University of Kent as a simple and inexpensive solution for reference signal reception in mm-wave radio-over-fibre base stations [1]. Because of the quantity of base stations required in picocellular networks, the cost of the components used is critical. The photoreceiver was thus designed for high power output with a minimum number of amplification stages, again reducing the cost.

The aim of this work was to make a noise analysis of the photoreceiver and find the possibilities for improvement of the noise performance. In order to do this, the photoreceiver equivalent circuit shown in Figure 1 has been used. I_s is a photocurrent source, C_j – photodiode p-n junction capacitance, R_s – photodiode bulk semiconductor resistance, C_p – photodiode package capacitance, L_w – bondwire inductance, R_l – load resistance (seen through step transformer). In Figure 1 it has been assumed that the device capacitance is equally distributed between the junction capacitance and the package (stand-off) capacitance. It will be shown in this work that the nature of the device capacitance is crucial in the design of low-noise receivers.

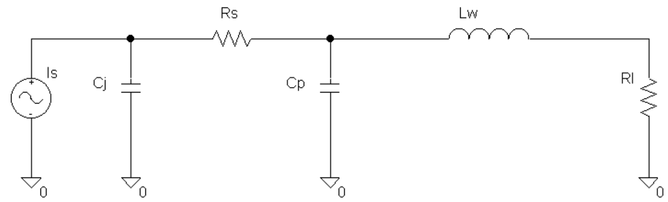

Figure 1 Photoreceiver equivalent circuit.

2. Noise analysis of the original circuit

In order to perform a noise analysis the circuit's transfer functions for signal and all noise sources need to be found. Two noise sources are considered:

1. Shot noise generated in the photodiode p-n junction,
2. Thermal noise generated in the bulk semiconductor resistance.

Because the signal and shot noise are generated at the same point in the circuit, the transfer function for them will be the same. The graphs of the signal and noise transfer functions devised in [1] are shown in Figure 2. The graphs in the figure are normalised for easier comparison.

Because the circuit was designed to receive a reference frequency, an unmodulated single tone is used as the signal. The noise on the other hand should be integrated over a certain bandwidth. The 3dB bandwidth of the signal transfer function was taken. Since the spectrum outside the 3dB bandwidth will not be used for signal transmission due to rapid Signal-to-Noise Ratio deterioration, it is possible to insert a bandpass filter after the circuit to suppress the noise outside this frequency range.

Using the equations and values of the parameters presented in [1] it is possible to find the minimum optical signal power P_{min} required to obtain 30 dB Signal-to-Noise Ratio at the output of the circuit. A 30 dB output SNR was taken as estimated minimum for successful use of the received reference tone. The noise figure of the amplifier was assumed to be 8dB (the noise figure of the Hewlett Packard amplifier used in the receiver). The result of the calculations is that $P_{min} = -16.9$ dBm, For comparison, the sensitivity of a 12 Gb/s photoreceiver with similar bandwidth, as described in [2], is –17.7 dBm.

A method for noise performance improvement is discussed in the following section.

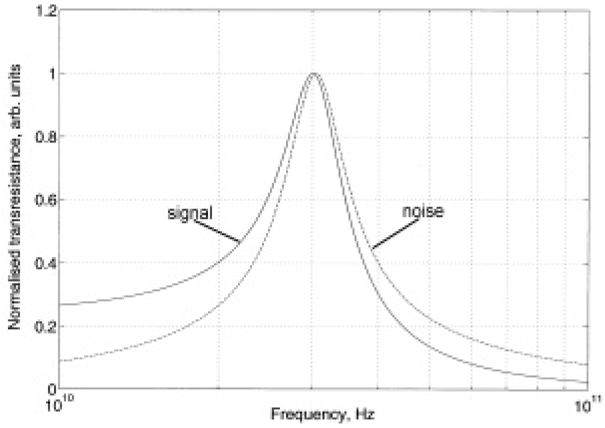

Figure 2 Signal and noise transfer functions.

3. Improvement of noise performance

3.1. Theory

As can be noticed from the graph in Figure 2, although the resonance frequency is the same for both signal and thermal noise there is a difference in the peak frequencies of the signal and noise transfer functions. This is because thermal noise has the additional term ($j2pR_sC_j$) a differential operator that shifts the peak frequency of the noise transfer function towards higher frequencies. (This shows that the circuit behaves as a differentiator for thermal noise.) If the circuit in Figure 1 is redrawn, as shown in Figure 3, it should become clear that the R_s C_j pair works as a differentiator for the equivalent thermal noise current I_{th}.

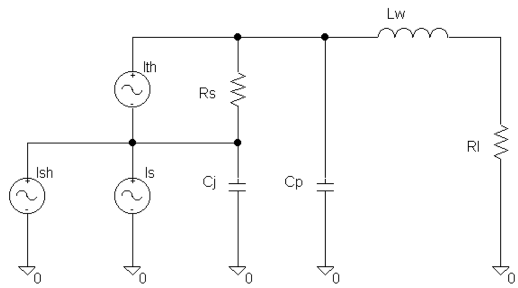

Figure 3 Photoreceiver equivalent circuit alternative representation.

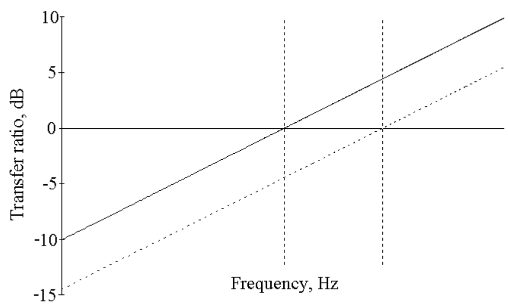

Figure 4 Transfer function of differential operator.

The transfer function of differentiator is shown in Figure 4. The value $T = R_s\ Cj$ defines where the function crosses 0dB. Thus, if the product $R_s\ Cj$ is decreased the frequency at which the graph crosses the x-axis will move to the right (dotted line), effectively decreasing the amount of noise power transferred to the output without affecting the signal. This conclusion fully agrees with the results of PSpice and MDS simulations.

This factor can be used to lower the thermal noise contribution to the total noise power and thus reach the theoretical limit of optical signal reception. Note that it does not matter which parameter R_s or C_j (or both) are reduced, as long as the product $R_s\ C_j$ is as low as possible.

3.2. Theoretical results

To find out how much improvement is possible from reducing the R_sC_j product, the noise analysis was repeated using values of R_s and C_j at several points between the original and technologically achievable ones. The results are shown in Figure 5 and Figure 6. For each value of R_sC_j, the bandwidth was tuned to be the same as that in the original circuit (7.35 GHz) by varying the C_p and L_w

parameters. The parameters were swung as follows: C_p = 0.4 pF to 5 pF, L_w = 5 pH to 70 pH.

As can be seen from the graphs in Figure 5, thermal noise from resistor *Rs* is the dominant noise source in the original circuit. But as soon as the *RsCj* product falls below 80 femtoseconds, shot noise becomes dominant. By further reducing *RsCj* (to a value of approximately 5 fs) shot noise limited reception is achieved. It does not make any sense to reduce *RsCj* below this level since thermal noise is no longer making significant contribution towards the total noise power. The same result is visible from the graph in Figure 6. The graph saturates in the region beyond the 5 femtoseconds point, and reducing R_sC_j does not bring any significant improvement to noise performance. The improvement of the sensitivity is 7.2dB.

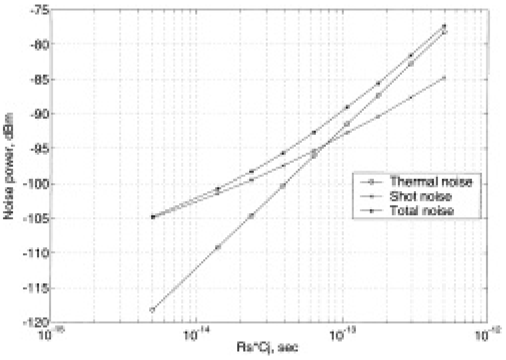

Figure 5 Noise power versus R_sC_j product.

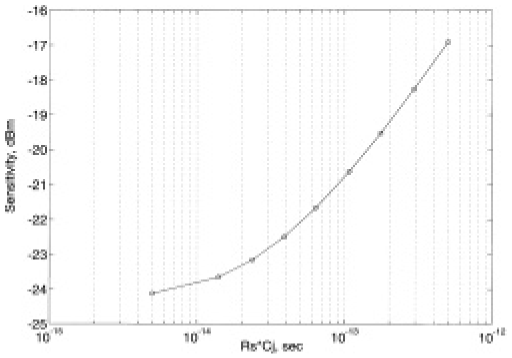

Figure 6 Optical power sensitivity of the circuit versus R_sC_j product.

4. Noise vs. Bandwidth

Because the bandwidth of the step transformer is limited and the bandwidth of the resonant circuit is much larger, it is worth looking at how the noise performance is affected by changing the passband. The bandwidth of the resonant circuit is varied by changing the *Lw* and *Cp* parameters, which do not affect the noise performance. The results of the calculations are shown in Figure 7 and Figure 8.

It can be seen from the graph in Figure 8 that the noise performance is improved by reducing the bandwidth. Thus, it is worth seeing how much bandwidth the step transformer can provide and matching the bandwidth of the resonant circuit to that of step transformer.

From the noise power graph in Figure 7 it can be seen that the thermal noise contribution increases with reducing bandwidth. Thus the *RsCj* product can be further reduced when the bandwidth is narrower and the receiver's noise performance is no longer shot noise limited.

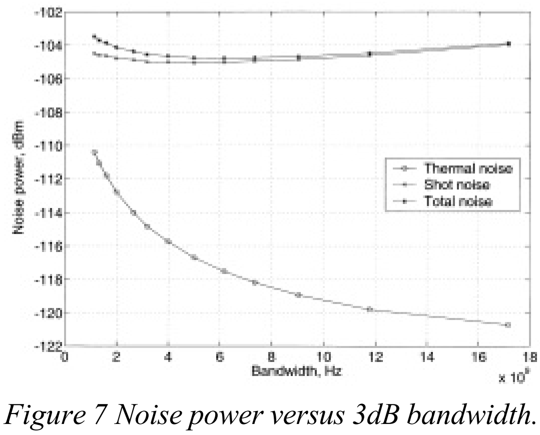

Figure 7 Noise power versus 3dB bandwidth.

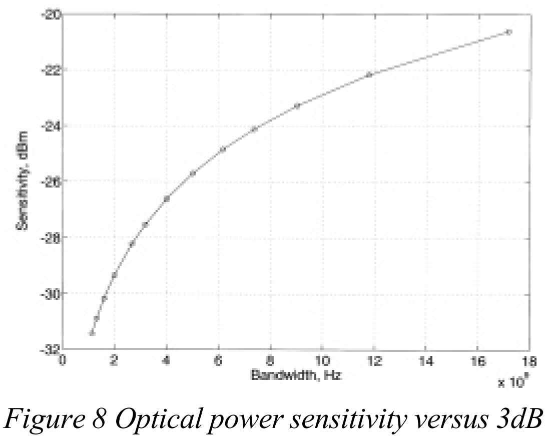

Figure 8 Optical power sensitivity versus 3dB bandwidth.

5. Noise vs. Load Resistor R_l

The load resistor directly affects the noise performance by affecting the signal transfer function thus, increasing load resistance should increase the power fed into the amplifier. In the previous section, the amplifier noise has not been taken into account to make discussion more clear. Now amplifier noise becomes the dominant noise source and the signal power output of the circuit is therefore critical. The signal transfer function is proportional to the value of R_l, so increasing R_l increases the amount of power transferred. However, the same resistor together with photodiode series resistor R_s reduces the Q-factor of the resonant circuit.

There is an optimum value of the load resistor R_l. The load resistor was swung from 10Ω to 110Ω with 10Ω step and the sensitivity was calculated for each value. An estimated minimum technologically achievable value for package capacitance C_{pmin} was set (see Figure 9). Bondwire inductance L_w and package capacitance C_p were used to tune the centre frequency and bandwidth where possible. If tuning the bandwidth required C_{pmin} to be less than C_p then only L_w was used to tune the centre frequency.

The results are shown in Figure 9. The sensitivity increases with increasing load resistance up to the point where value of C_p is no longer technologically achievable (less than C_{pmin}). Beyond that value of R_l, the damping effect decreases the sensitivity.

The analysis has been done for two values of C_{pmin} 10fF and 15fF and two values of bandwidth 4GHz and 6GHz. The lower the capacitance the higher sensitivity can be achieved because higher load resistance can be used maintaining same Q-factor. The lower the bandwidth the higher the sensitivity simply because less noise power passes through to the amplifier.

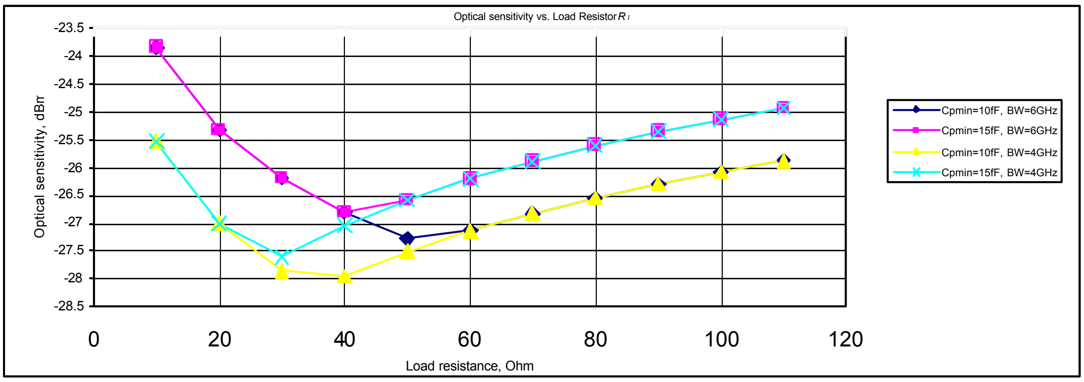

Figure 9 Optical sensitivity vs. load R_l.

6. Conclusion

A noise analysis has been performed for the matched photodiode-amplifier circuit of [1] and its optical power sensitivity was found. As a result of the analysis, it was found that a noise performance improvement allowing a 7.2 dB reduction of minimum optical signal power can be achieved without bandwidth alterations (original bandwidth is 7.35 GHz). Further, it is shown that a 12.4 dB improvement can be achieved by reducing the bandwidth down to 2 GHz to match the bandwidth of the step transformer designed in [1]. It has also been found that higher load resistance can increase sensitivity of the circuit if same Q-factor can be maintained using package capacitance and bondwire inductance as tuning elements.

7. References

1. L.Gomez-Rojas, X.Wang, N.J.Gomes, P.A.Davies, 'Efficient photoreceiver for millimetre-wave cellular system base stations', *International Topical Meeting on Microwave Photonics*, MWP2000, Technical Digest, pp. 194-7, Oxford, UK, Sept. 2000.
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3. K.L.Alameh, R.A.Minasian, 'Tuned Optical Receivers for Microwave Subcarrier Multiplexed Lightwave Systems', *IEEE Trans Microwave Theory and Techniques*, vol. 38, no. 5, pp. 546-51, May 1990.