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Optical Receiver for Optical Time Domain Reflectometer

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***Abstract*—In this paper we analyze an optical receiver (OR) for the optical time domain reflectometer (OTDR). Using optical receiver's model, which consists of shunt-shunt feedback transimpedance amplifier (TIA) and InGaAs avalanche photodiode (APD), we discuss and give equations for all important noise sources, which are amplifiers input transistor channel thermal and flicker noises, avalanche photodiode noise and feedback resistors noise. Than in terms of OTDR parameters, we explain the need of TIA variable gain, define the range of bandwidths, and introduce optimal values for OR dynamic range, APD multiplication and feedback resistance. Using these values we give an OR reference design and analyze received results.**

***Index Terms* —Circuit noise, CMOS integrated circuits, optical receiver.**

I. INTRODUCTION

Optical time domain reflectometer (OTDR) is an opto-electrical device used for optical fiber testing. It consists of four main parts: laser pulse generator, optical receiver (OR), DSP and display unit. The OTDR functions as follows: A laser pulse with a certain power *P* and width *PW* is feed into an optical fiber. Due to Rayleigh scattering a part of light start to travel in the opposite direction and is detected and converted into an electrical signal by optical receiver (OR). Finally, the signal is processed, analyzed and measurement results are displayed on the screen [1].

There are two important OTDR parameters that are strongly related: attenuation dead zone (ADZ) and dynamic range (*DR*) [1]. Attenuation dead zone is a specification defining minimum distance after a certain reflective event after which OTDR can measure a reflective or non-reflective event loss. It mainly depends on pulse width and bandwidth of the optical receiver. Dynamic range is a measure of OTDR sensitivity and shows the amount of optical loss and respectively the fiber length that device can analyze. As well as ADZ, dynamic range depends on the pulse width and bandwidth, and additionally on laser pulse power and gain of the optical receiver. Therefore, it is very important to achieve high dynamic range for a given attenuation dead zone.

Various parameters and principal of operation of an optical receiver for optical communication are well covered in the literature [2]–[4]. In this paper noise and main parameters of an OR for the OTDR are analyzed. Using a known noise model of an optical receiver [2] we define and calculate its optimal parameters that allow achieving best performance for each OTDR attenuation dead zone value.

II. OPTICAL RECEIVER STRUCTURE AND NOISE MODEL

The structure of an optical receiver used for noise calculations is shown in Fig. 1. It consists of InGaAs avalanche photodiode (APD) and shunt-shunt feedback topology transimpedance amplifier (TIA), which in turn consists of a voltage amplifier A_0 and feedback resistance R_f.

Three main noise sources are shown on Fig. 1. They are: resistor thermal noise, avalanche photodiode noise and voltage amplifier noise.

In order to perform noise analysis all noise sources have to be recalculated to equivalent input noise current spectral densities and combined into a single noise source.

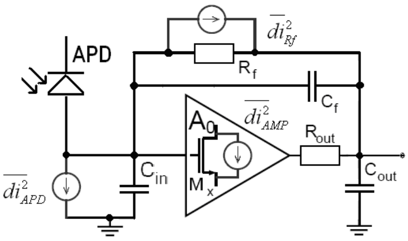

Fig. 1. Optical receiver with noise sources.

Feedback resistor R_f thermal noise is generated by the thermal agitation of the charge carriers that occurs inside any electrical conductor. It depends on a resistance value and temperature. Equivalent input noise current spectral density is calculated from the equation [5]

$$\overline{i^2}_{nRf} = \left(4\cdot k\cdot T\cdot \frac{1}{R_f}\right), \tag{1}$$

where k – Boltzmann constant, T – temperature, R_f - resistance.

An avalanche photodiode differs from the simple PIN photodiode by providing internal photo-electronic signal gain (*M*). Like a PIN detector APD has a shot noise, which derives from the random statistical Poissonian fluctuations of the dark current that is normally given by $I_{dn} = (2\cdot e\cdot BW\cdot I_D)^{1/2}$. APD has an additional noise component – bulk leakage current I_{dm}, that is called APD multiplied

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dark current. It is multiplied by the gain *M* and also depends on the noise excess factor *x*. The avalanche photodiode equivalent input noise current spectral density can be calculated from

$$\overline{i^{2}}_{nAPD} = 2 \cdot e \cdot \left(I_{dn} + I_{dm} \cdot M^{2+x} \right), \qquad (2)$$

where *e* – electron charge, I_{dn} – not multiplied dark current, I_{dm} – multiplied dark current, *M* – multiplication, *x* –excess noise factor.

For our calculations we used CEL InGaAs APD (NR8300FP-CC) data [6].

Voltage amplifier noise can be modeled as an input transistor noise. It consists of the two main parts: channel thermal noise and flicker (*1/f*) noise [7]. MOS transistor channel can be modeled as a resistor, therefore, its thermal noise has the same origin as resistor's thermal noise. Its equivalent input noise current spectral density, recalculated to transistor gate, is calculated from the equation [3]–[8]

$$\overline{i^{2}}_{TCh} = \left(2 \cdot \pi \cdot BW \right)^{2} \cdot C_{GS}{}^{2} \cdot \left(4 \cdot k \cdot T \cdot \frac{2}{3} \cdot \frac{1}{g_{m}} \right), \qquad (3)$$

where *k* – Boltzmann constant, *T* – temperature, g_{m} – transconductance, C_{GS} – gate-source capacitance, *BW* – bandwidth.

Flicker or *1/f* noise is strongly depends on the technology [9]. In our calculations we used simplified SPICE2 noise model that provides result not as accurate as BSIM3v3 model, but suits better for the hand calculations. *1/f* noise equivalent input noise current spectral density, as well as channel thermal noise recalculated to transistor gate, is given by [3]–[8]

$$\overline{i^{2}}_{T1/f} = \left(2 \cdot \pi \cdot BW \right)^{2} \cdot C_{GS}{}^{2} \cdot \left(\frac{Kf \cdot I_{DS}{}^{\alpha f}}{Cox \cdot L^{2} \cdot BW} \right), \qquad (4)$$

where *k* – Boltzmann constant, *T* – temperature, *Kf* – flicker noise constant, *αf* – flicker exponent, I_{DS} – channel current, C_{ox} – oxide sheet resistance, *L* – transistor length, C_{GS} – gate-source capacitance, *BW* – bandwidth.

Other transistor noise sources, like gate leakage current, which has higher rates in sub 100nm CMOS technologies, are not taken into account due to their low impact on overall noise.

For calculations shown in this article we use SMIC CMOS 0.13μm technology BSIM3v3 model parameters.

III. OTDR PARAMETERS

For each OTDR laser pulse width we can define a desirable attenuation dead zone. Knowing pulse width and desired ADZ length we can calculate impulse response and bandwidth of an optical receiver for each pulse width respectively. Table I shows an example of OR bandwidth calculation results for given ADZ values.

There are two ways to achieve certain bandwidth. First is to apply digital or analog filtering, and second is to increase feedback resistance of the transimpedance amplifier. If bandwidth of the white noise is decreased *x* times using filtering, the noise voltage decreases 1/√*x* times, and that means SNR increases √*x* times. If we increase feedback resistance *x* times we decrease bandwidth for the same amount, what gives 1/√*x* times smaller noise voltage, and additionally increase the output signal *x* times, what gives us *x*√*x* higher SNR. Therefore having a different feedback resistance value for every pulse width, which means variable gain, allows achieving better performance compared to simple filtering.

TABLE 1. TIA BW CALCULATION RESULTS.

PW, ns	**BW, MHz**
3 ns	110
5 ns	71
10 ns	39
30 ns	16
100 ns	5,6
300 ns	2,2
1 μs	0,8
3 μs	0,3
10 μs	0,1
20 μs	0,06

In order to get a higher dynamic range noise should be minimized. Noise analysis and optimization is shown in the next section. Calculation results are given in terms of OTDR single measurement dynamic range

$$DR = 5 \cdot \log\left(S / N \right), \qquad (5)$$

where *S* is a maximum signal level at the output of a TIA and it can be calculated as follows

$$S = Bs \cdot T \cdot P \cdot \eta \cdot M \cdot R_{f}, \qquad (6)$$

where *Bs* – Fiber backscatter coefficient for a given wavelength (-79dB@(1mW, 1ns) for 1310nm wavelength), *T* – laser pulse width, *P* – laser pulse power (50mW), *η* – APD quantum efficiency (0.9A/W), *M* – APD multiplication factor. Values used for numerical calculations are given in brackets

N is a noise level at the TIA output. Noise level can be found by multiplying total equivalent input noise current by TIA gain R_{f} ($N = i_{\mathrm{tot}} \cdot R_{\mathrm{f}}$). Total equivalent input noise current can be found by adding all equivalent input noise current spectral densities of all noise sources, multiplying by bandwidth and taking square root

$$i_{tot} = \sqrt{\left(\overline{i^{2}}_{nRf} + \overline{i^{2}}_{nAPD} + \overline{i^{2}}_{TCh} + \overline{i^{2}}_{T1/f} \right) \cdot BW}\ . \qquad (7)$$

IV. NOISE OPTIMIZATION

The first well known OR noise optimization issue is a TIA input capacitance. It was shown that best noise performance of TIA is achieved when amplifier's input capacitance is equal to all other parasitic input capacitances [10]. When reversed bias voltage, applied to an APD is above 30V, it has the highest parasitic capacitance value 0.35pF [6]. Knowing CMOS technology parameters this allows us to determine input transistor geometry and parameters for noise calculations.

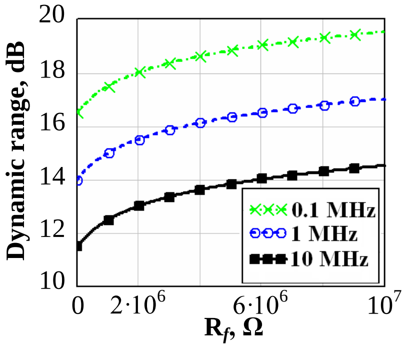

Fig. 2. Optical receiver dynamic range at different bandwidths when only R_f noise is taken into account (*PW*=100ns).

From (1) and (5) we can predict the behavior of feedback resistor noise current and its influence on dynamic range for different R_f values. As we defined in previous section, signal level is proportional to TIA gain – R_f. Voltage noise level at the output is proportional to square root of TIA gain multiplied by bandwidth. This means that signal to noise ratio and OTDR dynamic range are proportional to square root of R_f for a given bandwidth (Fig. 2). Thus, for each bandwidth optimal value of feedback resistance R_{opt} exists.

Another noise optimization issue is avalanche photodiode multiplication factor *M*. From the discussion above and (6) we can see that signal level is proportional to multiplication factor *M*, and noise proportional to M^{2+x}. While increasing APD multiplication factor *M* noise grows faster than signal. Optimal multiplication factor value M_{opt}, when overall noise is minimized, is defined as value when APD noise becomes equal to the sum of all other noise sources. M_{opt} value can be calculated using (8)

$$M_{opt} = \left(\left(\left(\frac{\overline{i^2_{nRf}} + \overline{i^2_{TCh}} + \overline{i^2_{T1/f}}}{2 \cdot e} \right) - I_{dn} \right) \frac{1}{I_{dm}} \right)^{\frac{1}{x+2}}. \qquad (8)$$

From (3) and (4) we can see that voltage amplifier input transistor's noise current does not depend on the feedback resistance value. That is why its noise voltage increases linearly with R_f. APD's optimal multiplication factor mostly depends on the transistor noise current for high R_f values (Fig. 3).

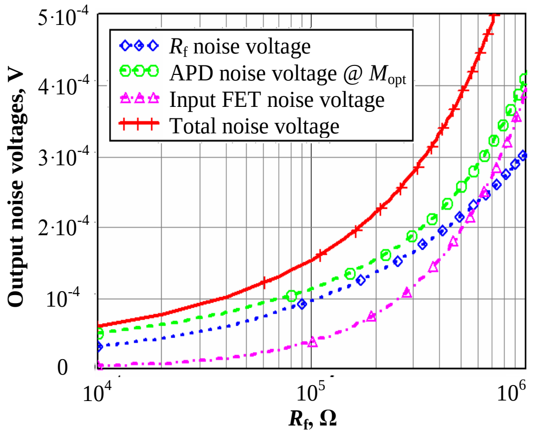

Fig. 3. Optical receiver noise voltages vs. R_f (*PW* = 100ns, *BW* = 5.6MHz).

This means that while increasing R_f after some point both, signal and overall noise start to grow almost linearly with feedback resistance and we observe only minor dynamic range increase (Fig. 4).

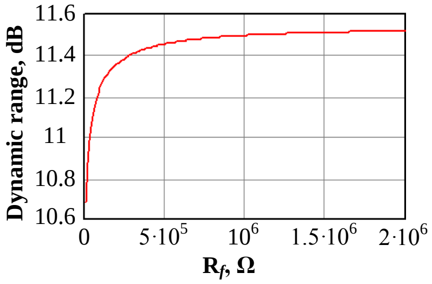

Fig. 4. Optical receiver dynamic range vs R_f (*BW*=5.6MHz, *PW*=100ns).

DR notably increases for R_f values up to 0,5MΩ. Further R_f growth adds to *DR* less than 0.1dB. On the one hand, in practice it is preferred to have lowest possible R_f because higher signal level will result in a more complex signal processing. On the other hand chosen R_f value must result in a near maximum *DR* value. We define optimal dynamic range for a given bandwidth as a value where *DR* is lower than the maximum by 0.05dB.

V. RESULTS

Optical receiver's dynamic range, optimal multiplication and feedback resistance over the bandwidth calculation results are shown on Fig.5.

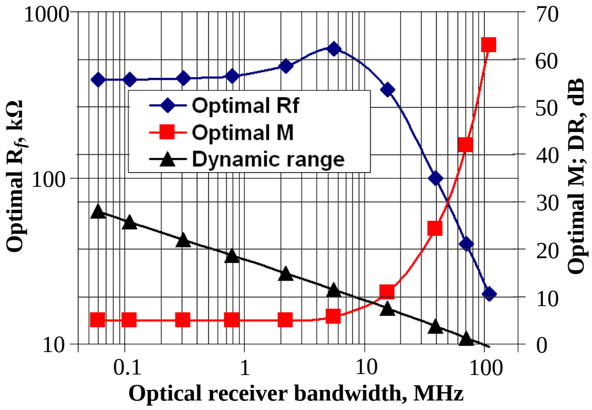

Fig. 5. Feedback resistance, APD multiplication and dynamic range optimal values vs. bandwidth.

All calculation results shown here are calculated for an optimal *DR* using (5). Moreover in signal level calculation (6) *PW* from Table 1 is taken into account for each *BW* and *DR* value.

These results can be explained with the help of Fig. 6, where input referred noise currents of all noise sources of an optical receiver over bandwidth are shown.

APD noise current is dominant almost over the all frequencies due to condition for M_{opt}, that it is defined by other noise sources.

At high frequencies (10-100MHz) OR overall noise is mostly defined by a voltage amplifier's input transistor channel noise which, as well as signal level, is linearly proportional to R_f. This means that at some point, where amplifier noise voltage starts to dominate over the feedback resistor noise, there is no increase in SNR and that is why the optimal R_f value is smaller for higher frequencies.

At middle frequencies (1-10MHz) nearly all noise sources, including flicker noise, are important. The dominant noise source becomes a feedback resistor.

At low frequencies (0.01-1MHz) R_f noise defines total noise level. Fig. 5 shows that in such situation optimal resistance value remains nearly constant. This is from the fact discussed in a previous section and shown on Fig. 2. When feedback resistor is dominant noise source all *DR* curves has the same shape for different bandwidths, therefore and optimal R_f values are the same. At low frequencies OR dynamic range is limited by a feedback resistor noise. This limitation is fundamental and impossible to overcome. In order to improve dynamic range at high frequencies, transimpedance amplifier noise should be minimized.

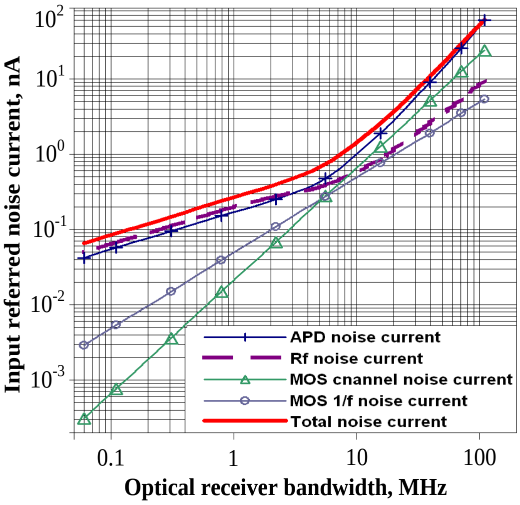

Fig. 6. Optical receiver input referred noise currents vs. bandwidth.

This can be achieved using more complex amplifier structures and more careful design. At the middle frequencies all noise sources are important and have more or less equal impact on the total noise. And again, noise can be reduced using different TIA design techniques.

VI. CONCLUSIONS

We analyzed optical receiver structure and noise model for an OTDR, gave equations for their input referred noise currents calculation, defined optical receiver's range of bandwidths and introduced optimal values for avalanche photodiode multiplication, transimpedance amplifier feedback resistance, and optical receiver dynamic range.

Altogether this gives an OR for OTDR analysis and design method, which allows to achieve optimal dynamic range with various types of photodiodes and amplifiers.

Using introduced method we perform calculations for OR particular case, and receive following results. APD gain M_{opt} is defined by overall noise, ranges from 63 to 5, and is highest at high frequencies. TIA optimal feedback resistance increment improves *DR* when other than resistor noise sources are dominating. At 5.6 MHz we have highest R_f value – 600 kΩ, because almost all noise sources are equally important. *DR* values ranges from 0dB for 3ns pulse and 110MHz bandwidth to 28 dB for 20 µs pulse width and 60 kHz bandwidth when laser pulse power is 50mW, backscatter coefficient is -79dB and averaging is not taken into account.

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