VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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TIME DOMAIN OPTICAL REFLECTOMETER SYSTEMS INVESTIGATION

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES,
ELECTRICAL AND ELECTRONIC ENGINEERING (01T)

Vilnius LEIDYKLA TECHNIKA 2013

Doctoral dissertation was prepared at Vilnius Gediminas Technical University in 2009–2013.

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The dissertation is being defended at the Council of Scientific Field of Electrical and Electronic Engineering at Vilnius Gediminas Technical University:

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The dissertation will be defended at the public meeting of the Council of Scientific Field of Electrical and Electronic Engineering in the Senate Hall of Vilnius Gediminas Technical University at 2 p. m. on 28 November 2013.

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The summary of the doctoral dissertation was distributed on 25 October 2013.

A copy of the doctoral dissertation is available for review at the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223 Vilnius, Lithuania).

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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LAIKO SRITIES OPTINIŲ REFLEKTOMETRINIŲ SISTEMŲ TYRIMAS

DAKTARO DISERTACIJOS SANTRAUKA

TECHNOLOGIJOS MOKSLAI,
ELEKTROS IR ELEKTRONIKOS INŽINERIJA (01T)

Vilnius LEIDYKLA TECHNIKA 2013

Disertacija rengta 2009–2013 metais Vilniaus Gedimino technikos universitete.
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Disertacija bus ginama viešame Elektros ir elektronikos inžinerijos mokslo krypties tarybos posėdyje 2013 m. lapkričio 28 d. 14 val. Vilniaus Gedimino technikos universiteto senato posėdžių salėje.

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Disertacijos santrauka išsiuntinėta 2013 m. spalio 25 d.

Disertaciją galima peržiūrėti Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).

VGTU leidyklos „Technika“ 2180-M mokslo literatūros knyga.

Introduction

Topicality of the problem

Nowadays over 90% of all long range data transmissions are carried out over the optical fibre channels. New technologies made high bandwidth Internet accessible to the users by bringing the optical fibre channels to user homes (FTTH) using passive optical networks (PON).

Optical time domain reflectometry is a type of optical fibre testing that is most widely used, permitting to measure all fibre channel parameters needed for its certification from one channel side. Optical time domain reflectometer (OTDR) has two main strongly related parameters: dynamic range and attenuation dead zone. A third parameter – input signal range, defines maximum signal level that a device can measure and is important as well.

Several types of optical channels exist. The first is point to point channel, for example, a connection between a end user and a local server. Such channel length can be as short as several meters, therefore requires the shortest attenuation dead zone. The second is a PON network, where due to the high optical splitter ratios a large signal loss is introduced. Thus, in order to measure such networks a high and known dynamic range is required. For a given dynamic range the highest possible bandwidth is needed. The third type is long haul optical channels, where dynamic range needs to be maximized.

OTDR must be optimized for each type of optical channel measurements, which means that for a given attenuation dead zone it has to provide an optimal dynamic range and accept a wide range of input signals.

Dynamic range can be increased by increasing laser pulse power and width, or in other words, by increasing energy fed into fibre. The laser pulse power is limited to 1 W by nonlinear Kerr effects. Pulse width broadening increases the dead zones, thus is ineffective for a dynamic range improvement. So, the only effective way to improve OTDR is to optimize its optical receiver's dynamic range for a range of bandwidths of interest. Due to these specific requirements of the OTDRs optical receiver, its design methodology is required, allowing calculating optical receiver's optimal dynamic range for a given set of bandwidths.

Object of research

The optical receiver of an optical time domain reflectometer.

Aim of the work

The main aim of this work is to create an optical receiver design methodology to achieve optimal dynamic range of the system for a given bandwidth, design and investigate integrated fully differential variable gain transimpedance amplifier for OTDR optical receiver.

Tasks of the work

The following tasks had to be solved to achieve the aim of the work:

1. Perform analysis of OTDR structures, main specifications and suggest possible improvement approaches.
2. Analyse main optical receiver noise sources and noise minimization and create generalized noise model.
3. Create optical receiver for an OTDR design methodology, that allow calculating avalanche photodiode multiplication factor, transimpedance amplifier feedback resistance and voltage amplifier input transistor dimensions that achieves optimal OTDR dynamic range.
4. Design optical receiver from discrete components and analyse its parameters.
5. Design and perform simulations of transimpedance amplifier integrated circuit using AMS 0.35 μm CMOS technology and calculate optical receiver parameters in 0.1–100 MHz range of bandwidths.

Methodology of research

The analytical, numerical and experimental methods were applied in the work. Calculations, optimization and mathematical model creation were performed with Matlab® and Mathcad®. Circuit design and simulations were performed with OrCad®, Cadence IC Design Suite® and other CAD software. Experimental research was performed using LabView®, designing new as well as upgrading existing hardware. The acquired results were compared with other commercially available OTDRs.

Scientific novelty

The following scientific novelties to the field of Electrical and Electronic Engineering were disclosed:

1. Theoretical and analytical investigation of the main optical receiver blocks and their noise characteristics, which mostly influences OTDR dynamic range, was carried out, resulting in the creation of a generalized noise model of an optical receiver.
2. Creation of OTDRs optical receiver design methodology for achieving optimal dynamic range by calculating avalanche photodiode multiplication factor, transimpedance amplifier feedback resistance and amplifier input transistor dimensions.

3. The design and investigation of the differential transimpedance amplifier with variable gain from 20 kΩ to 800 kΩ, and maximum 107 MHz bandwidth using 0.35 μm CMOS technology allowing to achieve 2 meters OTDR attenuation dead zone.

Practical value

The created optical receiver design methodology was applied during the improvement and in the new designs of commercial OTDR devices. Fully differential variable gain transimpedance amplifier is planned to be used in the next generation high resolution, 2 meters dead zone, and high dynamic range, up to 42 dB OTDR by the same commercial company.

Defended propositions

1. Created OTDR optical receiver noise model evaluates all most important noise sources and can be applied in OTDR research and design in order to calculate transimpedance amplifier feedback resistance, avalanche photodiode and input transistor geometry, which results in optimal dynamic range.
2. Proposed optical receiver design methodology allows to get optimal optical time domain reflectometer dynamic range, which gives reduced by 5% signal to noise ratio, and in 0.1–10 MHz bandwidths range increases measurable input signal span by 1.4–2.1 times, when optical receiver designed from discrete components.
3. Fully differential variable gain, from 20 kΩ to 800 kΩ transimpedance amplifier integrated circuit, designed in 0.35 um CMOS technology enhances bandwidth, which is in 0.1–107 MHz range, and achieves optical reflectometer 2 meters dead zone with 15 mW power consumption.

The scope of the scientific work

The dissertation consists of introduction, four chapters, summary, list of references, list of publications and one appendix.

The total scope of the dissertation is – 113 pages not including appendixes, 74 numbered formulae are used in text, 54 pictures and 13 tables. Bibliography consists of 103 literature sources.

1. Reflectometer system analysis

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_0 and width T_0 is feed into an optical fiber. Due to Rayleigh scattering a part of the light starts to travel in the opposite direction and is detected and converted into an electrical signal by optical receiver (OR). Finally, the signal is processed, analysed and measurement results are displayed on the screen (Fig. 1).

There are two important OTDR parameters that are strongly related: attenuation dead zone (ADZ) and dynamic range (DR). 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 laser 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 the device can analyse. As well as ADZ, dynamic range depends on the laser pulse width and bandwidth, and additionally on the 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. Another important OR characteristic is input signal range, that depends on the OR gain and defines maximum acceptable signal level.

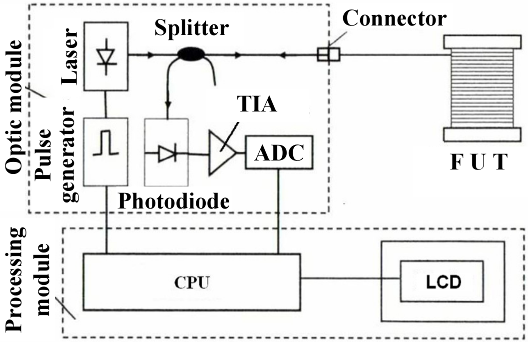


Fig. 1. The structure of conventional OTDR

In order to achieve the desired ADZ, it is possible to select pulsewidth and calculate OR bandwidth. Therefore, the main goal during OTDR optical receiver design is to optimize dynamic range for the range of given bandwidths. A common set of pulsewidths used in OTDR measurements ranges between 5 ns and 20 µs, which requires OR bandwidth from 100 MHz to 100 kHz respectively.

In order to compare the performance of different optical receivers the dynamic range of OTDR should be normalized to 1 mW laser power, 1 ns pulse width and 1 measurement, which means no signal averaging is performed. Also the bandwidth of the receivers must be the same. Table 1 shows normalized dynamic range calculation results of the most popular OTDR models. Measured dynamic range row shows dynamic range measured at 1310 nm wavelength with lowest bandwidth, which is shown in second row.

Table 1. Comparison of specifications of an optical time domain reflectometers

OTDR model Parameter	LIFODAS FLX380	EXFO FTB7300e	JDSU 4146
Measured dynamic range, dB	38	39.4	38.2
Lowest bandwidth, MHz	0.1	0.5	0.15
Normalized dynamic range, dB	-0.27	-0.1	-1.03
Shortest attenuation dead zone, m	3.5	4	4
Highest bandwidth, MHz	50	36	36

By knowing the shortest dead zone, pulse width and reflection coefficient it is possible to calculate the maximum OR bandwidth. These results are also shown in the Table 1.

2. Design methodology for optical time domain reflectometer optical receiver

The structure of an optical receiver used for noise calculations is shown in Figure 2 (a). It consists of InGaAs avalanche photodiode (APD) and shunt-shunt feedback topology transimpedance amplifier (TIA) that in turn consists of a voltage amplifier A_v and a feedback resistance R_f.

Four main noise sources are shown on Figure 2 (b). They are: resistor thermal noise i_{nRf}, avalanche photodiode noise i_{napd}, voltage amplifier voltage e_{ni} and current i_{nd} noise.

In order to perform noise analysis all noise sources have to be recalculated by combining them into a single noise source.

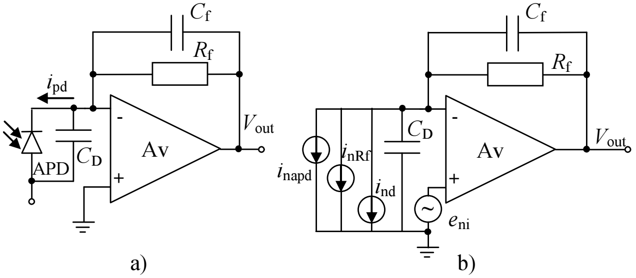


Fig. 2. Optical receiver: a) simplified schematics and b) noise model

The proposed generalized noise model defines total optical receiver output noise voltage $E_{\text{no-tot}}$ and takes into account all most important noise sources where dependence on various parameters is given by (1).

$$E_{\text{no}-\text{tot}} = \left\{ \sqrt{\begin{array}{l} E_{\text{noR}}\left(i_{\text{nRf}}, R_{\text{f}}, B\right)^2 + \\ E_{\text{npd}}\left(i_{\text{napd}}, M, R_{\text{f}}, B\right)^2 + \\ E_{\text{noI}}\left(i_{\text{nd}}, C_{\text{T}}, C_{\text{D}}, R_{\text{f}}, B\right)^2 + \\ E_{\text{noE}}\left(e_{\text{ni}} R_{\text{f}}, C_{\text{f}}, A_{\text{n}}, B\right)^2 \end{array}} \right. , \qquad (1)$$

where E_{noR} – resistor output noise voltage; E_{npd} – photodiode output noise voltage; E_{noI} – voltage amplifier equivalent input noise current recalculated to output noise voltage; E_{noI} – voltage amplifier equivalent input noise voltage, recalculated to output noise voltage; M – avalanche photodiode multiplication factor; C_{T} – voltage amplifier input transistor capacitance; C_{D} – detector capacitance; A_{n} – voltage amplifier DC voltage gain; B – bandwidth.

Noise model analytically shows that voltage amplifier input transistor and detector capacitance ratio, which minimizes the noise, is equal to 1.

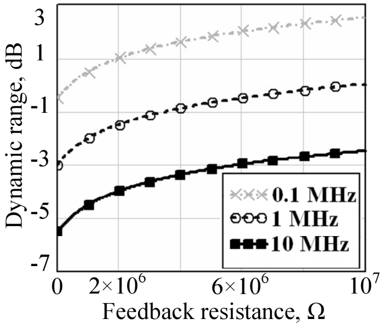
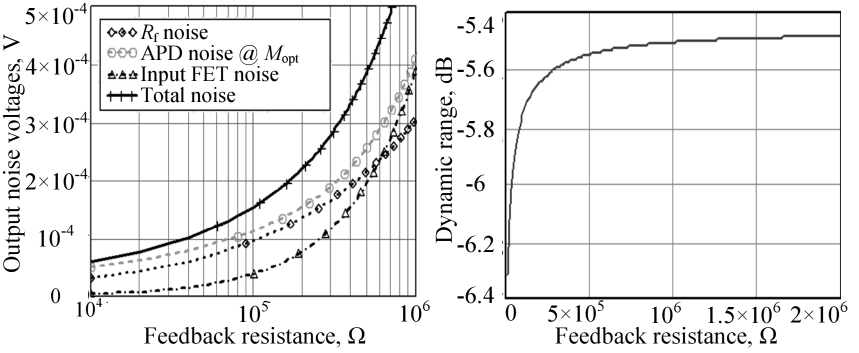


Fig. 3. Optical receiver normalized dynamic range calculation example at different bandwidths when only feedback resistor noise is taken into account

According to the created model transimpedance amplifier feedback resistor noise dominates at the low bandwidths. If it is the only noise source, then normalized dynamic range has square root dependence on resistor value at all frequencies (Fig. 3). At high bandwidths voltage amplifier noise dominates. It is almost independent of a R_{f} value, which means that while increasing R_{f} value, noise and signal increases with same rate, so there is no dynamic range enhancement.

Choosing right avalanche photodiode multiplication factor M results in the highest OR dynamic range. The signal level is proportional to multiplication factor M, and the noise is proportional to M^{2+x}, where x is an excess noise factor. While increasing APD multiplication factor M the noise grows faster than the signal. Optimal multiplication factor value M_{opt} exists, and is achieved, when APD noise becomes equal to the sum of all other noise sources. In optical receiver with optimal multiplication factor the overall noise is defined by other than APD noise sources.

The optical receiver output noise voltage calculation example is shown in Figure 4 (a). Figure 4 (b) shows calculated normalized dynamic range. DR notably increases for R_{f} values up to 0.5 MΩ. Further increase of R_{f} results in the same signal and noise increase ratio, so only minor dynamic range increase is observed, which adds to DR less than 0.1 dB. In order to increase input signal range it is preferred to have the lowest possible R_{f}. On the other hand, chosen R_{f} value must result in a near maximum DR value. In this work optimal dynamic range is defined as a value where DR is lower than the maximum value by 0.1 dB.



a) b)

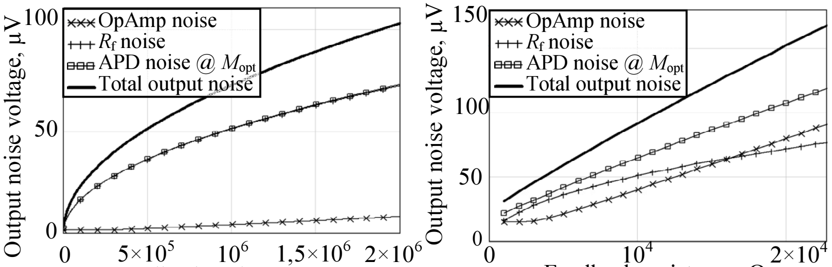
Fig. 4. Optical receiver a) noise voltages dependence on feedback resistance value at 5.6 MHz bandwidth, b) normalized dynamic range dependence on feedback resistance value when all noise sources are taken into account at 5.6 MHz badwidth

In order to design an optical receiver with optimal parameters the design methodology is proposed, and following steps have to be accomplished:

1. Choose and analyze optical receiver structure, choose or design its components taking into account needed range of bandwidths and production technology;
2. Calculate or simulate transimpedance amplifier noise dependence on feedback resistor value;
3. Calculate avalanche photodiode optimal multiplication factor dependency on transimpedance amplifier feedback resistance;
4. Calculate optical receiver output noise dependency on feedback resistance with optimal APD multiplication factor;
5. Calculate optical receiver normalized dynamic range dependency on feedback resistance with optimal APD multiplication factor;
6. Find the optimal dynamic range for each bandwidth of interest using suggested, 0.1 dB criteria;
7. Find optimal feedback resistance as well as avalanche photodiode optimal multiplication factor for each bandwidth of interest;
8. Having these optimal values perform a designed optical receiver results analysis.

3. Design and investigation of an optical receiver from the discrete components

In order to verify created optical receiver noise model, an OR test board from discrete components is designed. Transimpedance amplifier is based on OPA657 operational amplifier and has 4 switchable resistors, which results in 4 possible resistance values: 10 kΩ, 50 kΩ, 250 kΩ and 1000 kΩ.



a) b)

Fig. 5. Calculated optical receiver output noise voltage dependence on feedback resistance value with: a) 0.1 MHz bandwidth and b) 10 MHz bandwidth

Equivalent input voltage noise transfer function has small dependence on the feedback resistance value, so operational amplifier noise as TIA output slightly depends on R_f as well.

Calculated output noise voltages of main optical receiver blocks at various bandwidths are shown on Figure 5. Calculations show that at low bandwidths (Fig. 5 a), resistor noise dominates in total output noise, while at high bandwidths (Fig. 5 b) amplifier noise plays the most important role.

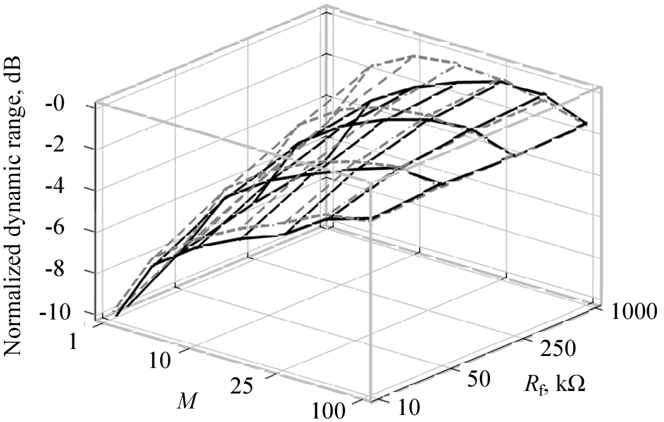


Fig. 6. Optical receiver calculated (grey, dashed) and measured (black) normalized dynamic range dependence on feedback resistor value and avalanche photodiode multiplication factor at 0.1 MHz bandwidth

Optical receiver normalized dynamic range calculation and measurement results when bandwidth is equal to 100 kHz, demonstrate good agreement (Fig. 6). Existing mismatches could appear due to external electromagnetic interference, but these mismatches influences only APD optimal multiplication factor value. Calculation and measurement results with other bandwidths show similar results. The maximum mismatch is 1.7 dB, and its average value does not exceed 0.5 dB.

Figure 7 shows the comparison of measured and calculated results of OR normalized dynamic range and APD optimal multiplication factor.

Despite the mismatch, shown on Figure 6, dynamic range with optimal multiplication factor measurement and calculation results shows excellent agreement. Maximum mismatch at all bandwidths is 0.23 dB, and its average value is less than 0.1 dB. The only difference is that due to external electromagnetic noise, the measured optimal photodiode multiplication factor is higher than the calculated one.

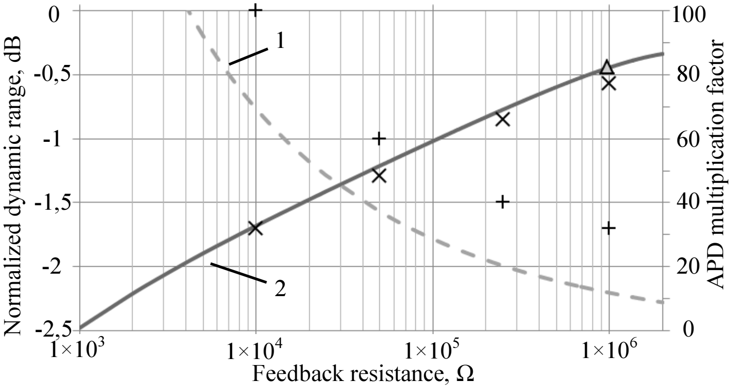


Fig. 7. Measured and calculated optical receivers normalized dynamic range and photodiode optimal multiplication factor dependence on feedback resistor value at 0.1 MHz bandwidth, where: 1 – calculated photodiode optimal multiplication factor, 2 – calculated normalized dynamic range with M_{opt}, "+" – measured photodiode optimal multiplication factor, "×" – measured normalized dynamic range with M_{opt}

Table 2 summarizes measurement and calculation results for 0.1–10 MHz bandwidths. Optimal measured and calculated feedback resistance values for various bandwidths match, and range from 10.3 kΩ at 10 MHz bandwidth to 970 kΩ at 0.1 MHz.

The analysis of the results shows that created noise model suites for optical receiver for OTDR optimal dynamic range and feedback resistance calculation. The maximum achieved normalized dynamic range is -0.44 dB. The only difference is that the optimal dynamic range is achieved with a higher multiplication factor. When optical receiver designed with the optimal dynamic range, the signal to noise ratio is reduced by 5%, but due to TIA feedback resistor value is reduced up to 2.1 times, the input signal range is increased by the same amount. That enables OTDR to measure events with a higher reflectance, and thus provides more precise measurements.

Table 2. Summary of measured and calculated optimal parameters

B, MHz	R_{fmax}, kΩ	R_{fopt}, kΩ	$R_{\mathrm{fmax}}/R_{\mathrm{fopt}}$	Calculated M_{opt}	Measured M_{opt}	DR
0.1	2000	970	2.1	11.6	32	-0.44
0.25	915	592	1.6	14.7	36	-1.6
0.5	460	320	1.4	19	42	-2.5
1	234	116	2	24	32	-3.4
10	23	10.3	1.9	80	100	-6.7

Designed optical receiver from discrete components maximum 20 MHz bandwidth is achieved with 10 kΩ feedback resistor. Other analyzed OTDRs have higher bandwidths, but it does not exceed 50 MHz and does not cover the whole range of bandwidths of interest (0.1–100 MHz).

4. Design and investigation of the variable gain transimpedance amplifier integrated circuit

In order to overcome the bandwidth limitations of an optical receiver from discrete components, to increase number of feedback resistances and improve immunity to external noise, a fully differential transimpedance amplifier with a variable gain integrated circuit was designed in AMS 0.35 µm CMOS technology using proposed design methodology.

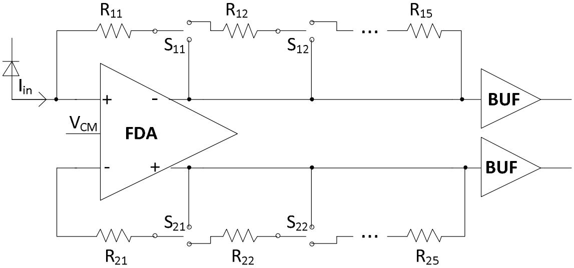


Fig. 8. The structure of fully differential transimpedance amplifier with variable gain

According to OR design methodology the first step is TIA structure selection and design of the necessary components. Selected transimpedance amplifier structure has 6 pairs of feedback resistors and is shown in Figure 8.

TIA design starts from fully differential amplifier (FDA) input transistor size calculations. It was shown, that TIA noise minimum is achieved when input transistor capacitance is equal to detector capacitance. Knowing detector capacitance (0.35 pF), technology parameters, like gate oxide sheet capacitance and thickness, when transistor length is 700 nm calculated input transistor width is equal to 110 µm.

In order to design stable transimpedance amplifier with zero percent overshoot, voltage amplifier gain bandwidth product (GBP) should be at least 4 times larger than a maximum optical receiver bandwidth. FDA includes β-multiplier based bias voltage generator, that stabilizes amplifier tail current, and has only 0.6 µA/V instability when supply voltage varies from 2.5 V to 3.5 V. The designed common mode circuit allows to set FDA common mode voltage from 0.9 V to 1.5 V. FDA output voltage is linear from 300 mV to 2.7 V, GBP is equal to 900 MHz, phase margin is 52°, and DC voltage gain is 60 dB. Current consumption from 3 V supply is equal to 4 mA.

SPDT switch, used to change TIA gain is made of a pair of simple transmission gates. Overall designed switch bandwidth is 1.2 GHz.

When voltage amplifier is designed, according to the proposed optical receiver design methodology a calculation of TIA noise dependence on feedback resistance at various bandwidths has to be performed. Having noise values an optimal multiplication factor is calculated. A third step is to calculate normalized dynamic range dependency on the feedback resistor values for different bandwidths and to and find optimal R_f.

Simulation and calculation results showed, that optimal feedback resistances ranges from 1.9 MΩ at 100 kHz bandwidth to 20 kΩ at maximum 100 MHz.

Taking into consideration factors like parasitic capacitance and size on chip, selected TIA feedback resistance values are 20 kΩ, 50 kΩ, 100 kΩ, 200 kΩ, 400 kΩ, 800 kΩ.

When all necessary TIA parameters are known, TIA topology was designed using AMS 0.35 μm CMOS technology and C35B3C3 process, that allows using high voltage MOS transistors, PIP capacitors and has high resistive poly module. The designed TIA die active area is 100 μm × 250 μm, where 50 μm × 90 μm area is occupied by resistors.

In order to get more accurate simulation results all parasitics were extracted from the topology. Simulated TIA gain with a small error corresponds to feedback resistor value, and a maximum achieved bandwidth is 107 MHz. Such a bandwidth allows to achieve an OTDR with 2 meters attenuation dead zone with 3 ns laser pulse width and -50 dB reflection.

After TIA noise dependence on feedback resistance value at various bandwidths simulation and optimal APD multiplication factor calculations, the optical receiver normalized dynamic range curves were calculated (Fig. 9). At low bandwidths (0.1–1 MHz) feedback resistance is limited by maximum available R_f value, so optimal values are set to it (800 kΩ). Such limitation has a negative impact on optical receivers dynamic range, which is becomes lower by 0.16 dB, but this also provides up to 4 times improved input signal range and reduces IC die size about two times. At bandwidths above 1 MHz additional R_f optimality criteria does not influence calculated results.

At higher bandwidths the maximum feedback resistance is limited by parasitic feedback capacitance. Also, voltage amplifier noise has higher impact, which means that the increasing R_f gives less signal to noise ratio and dynamic range improvement.

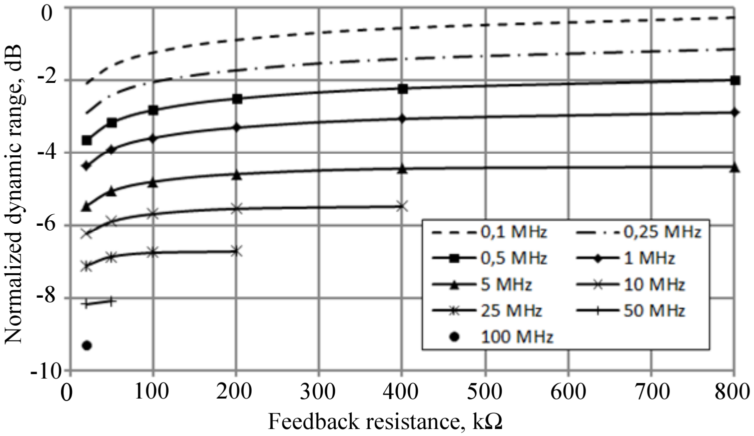


Fig. 9. Normalized dynamic range dependence on feedback resistance at various bandwidths with optimal avalanche photodiode multiplication factor

Normalized optimal dynamic range, optimal feedback resistance and multiplication factor are summarized in Table 3. The results show that for 0.1–100 MHz bandwidths range, the optimal feedback resistance ranges from 20 kΩ to 800 kΩ, and the optimal multiplication factor from 15 to 90. Normalized dynamic range at the lowest 0.1 MHz bandwidth is equal to -0.26 dB. Achieved dynamic range is almost the same as commercial FLX380 OTDR (-0.27 dB), and is better than commercial JDSU4146 OTDR (-1.03 dB).

Table 3. Summary of measured and calculated optimal parameters of an optical receiver based on transimpedance amplifier integrated circuit

B, MHz	R_{fmax}, kΩ	R_{fopt}, kΩ	$R_{\mathrm{fmax}}/R_{\mathrm{fopt}}$	M_{opt}	DR
0.1	3200	800	4	17.1	-0.26
0.25	3200	800	4	16.2	-1.13
0.5	3200	800	4	15.8	-2
1	3200	800	4	15	-2.9
5	800	400	2	20.4	-4.4
10	400	200	2	27	-5.5
25	200	50	4	47.5	-6.8
50	50	20	2.5	80.5	-8.2
100	20	20	0	90	-9.3

The designed differential transimpedance amplifier integrated circuit overcomes bandwidth limitations of TIA, designed from discrete components and has a similar dynamic range. Monte Carlo worst case power supply rejection ratio is not worse than 250 dB at 1 kHz when 100 iterations are simulated. Total IC area is 0.025 mm^2, current consumption is about 5 mA from 3 V supply.

General conclusions

1. This work performed the analysis of the optical reflectometer structures and their main parameters. As a result, conventional optical time domain reflectometer is most widely used for optical testing due to its measurement accuracy and reliability. A method of improving OTDR was formulated: OTDRs optical receiver dynamic range optimization, input signal range broadening and attenuation dead zone minimization.
2. The structure of the optical receiver was analysed, discussing the most important noise contributors and giving analytical expressions for their calculation. In order to perform further analysis, generalized noise model of an optical receiver was created.
3. An optical receiver for OTDR design methodology based on the noise model was created. This methodology allows calculating avalanche photodiode multiplication factor, transimpedance amplifier gain and input transistor geometry that provides an optimal dynamic range of the optical receiver. Optimal dynamic range gives smaller signal to noise ratio by 5%, but provides up to several times reduced feedback resistor value and broadens input signal range by the same amount.
4. The optical receiver from the discrete components was designed, and the experiment was carried out. Calculation and measurement results comparison shows that their average difference is only about 0.1 dB, suggesting that proposed methodology suites well the optimal feedback resistor for a given bandwidth calculation, and provides an optimal dynamic range.
5. In order to extend the bandwidth to 100 MHz, a design and investigation were performed on 0.35 μm CMOS fully differential variable gain transimpedance amplifier with 0.1–100 MHz bandwidth, 20–800 kΩ variable feedback resistance, and 107 MHz maximum bandwidth. Due to the higher bandwidth it also allows to achieve OTDR 2 meter attenuation dead zone when 3 ns laser pulse width and -50 dB reflection is used.

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LAIKO SRITIES OPTINIŲ REFLEKTOMETRINIŲ SISTEMŲ TYRIMAS

Mokslo problemos aktualumas

Daugiau nei 90 procentų viso duomenų srauto, siunčiamo ilgais atstumais, perduodama naudojant optinius tinklus. Didėjantis interneto greičio poreikis galutiniam vartotojui sąlygojo technologijų atsiradimą, kuomet šviesolaidis atvedamas į vartotojo namus (FTTH) naudojant pasyvius optinius tinklus (PON). Pastarojoje technologijoje naudojami optinio signalo šakotuvai, kurie vieną skaidulą šakoja į daugelį optinių skaidulų. Dalybos koeficientas būna nuo 2 iki 256.

Sudėtingėjant informacijos perdavimo technologijoms, optinio kanalo kokybei ir atitinkamai optinės skaidulos testavimo įrangai kyla vis aukštesni reikalavimai. Optinė reflektometrija yra plačiausiai taikoma optinės linijos testavimui, nes iš vienos optinės skaidulos galo su vienu prietaisu įmanoma išmatuoti visus optinės skaidulos parametrus būtinus sertifikavimui ir optinės linijos eksploatavimui.

Optinis kanalas gali būti kelių rūšių: tiesioginis tarppunktis kanalas, kurio ilgis būna iki kelių metrų, todėl reikalinga trumpiausia reflektometro nejautrumo zona. Antras – PON tinklai, kur dėl šakotuvų didelio dalybos koeficiento, žinomam dinaminiam diapazonui, reikia siekti trumpiausios nejautrumo zonos. Trečias – tolimojo ryšio optiniai kanalai, kurių matavimams reikalaujamas kuo didesnis reflektometro dinaminis diapazonas.

Vienintelis efektyvus būdas patobulinti laiko srities optinį reflektometrą yra optinio imtuvo parametrų optimizavimas pagrindinėms optinio kanalo rūšims, t. y. nejautrumo zonos minimizavimas ir dinaminio diapazono optimizavimas reikalaujamoms dažnių juostoms atsižvelgiant į matuojamų signalų diapazoną. Šie uždaviniai yra aktualūs ir turi praktinę vertę.

Tyrimų objektas

Darbo tyrimų objektas – laiko srities optinių reflektometrinių sistemų optiniai imtuvai.

Darbo tikslas

Sukurti reflektometro optinio imtuvo projektavimo metodiką, leidžiančią pasiekti optimalų dinaminį diapazoną duotajai dažnių juostai, suprojektuoti ir ištirti integrinį diferencinį pereinamos varžos stiprintuvą su kintamu stiprinimo koeficientu.

Darbo uždaviniai

Darbo tikslui pasiekti sprendžiami šie uždaviniai:

1. Atlikti optinių reflektometrų struktūrų ir jų pagrindinių charakteristikų analizę, ir suformuluoti tobulinimo kryptis.
2. Išanalizuoti pagrindinius optinio imtuvo triukšmų šaltinius ir jų mažinimo galimybes, sudaryti apibendrintą optinio imtuvo triukšmų modelį.
3. Sukurti optinio imtuvo projektavimo metodiką, leidžiančią apskaičiuoti griūtinio fotodiodo dauginimo faktorių, pereinamosios varžos stiprintuvo grįžtamojo ryšio varžą ir įėjimo tranzistoriaus fizinius matmenis, kuriems esant gaunamas optimalus dinaminis diapazonas.
4. Suprojektuoti optinio imtuvo maketą iš diskrečiųjų elementų ir ištirti jo parametrus.
5. Atlikti integrinio pereinamos varžos stiprintuvo projektavimą ir modeliavimą, taikant 0,35 μm KMOP technologiją bei optinio imtuvo parametrų skaičiavimą 0,1−100 MHz dažnių juostoje.

Tyrimų metodika

Darbe naudojami analitiniai ir skaitiniai tyrimo metodai. Skaičiavimams, optimizavimui ir matematinių modelių sudarymui buvo naudoti Mathcad® ir Matlab® programų paketai. Schemų projektavimui ir gautų parametrų modeliavimui taikyti automatizuoto projektavimo programiniai paketai Cadence OrCAD®, Cadence IC Design Siute® ir kiti. Eksperimentiniai tyrimai buvo atlikti naudojant LabView® programų paketą, integruojant naujus blokus į egzistuojančias reflektometrinės sistemas arba jas modifikuojant. Gauti rezultatai palyginami su kitų autorių darbais ir komercinėmis sistemomis.

Mokslinis naujumas

Rengiant disertaciją buvo gauti šie elektros ir elektronikos inžinerijos mokslui nauji rezultatai:

1. Teoriškai ir analitiškai ištirtos pagrindinių elementų, labiausiai įtakojančių optinio imtuvo, skirto laiko srities optinei reflektometrijai, dinaminį diapazoną, triukšminės charakteristikos ir sudarytas apibendrintas optinio imtuvo triukšmų modelis, kuris leidžia įvertinti kiekvieno triukšmo šaltinio įtaka suminiam triukšmui.
2. Sukurta optinio imtuvo, skirto laiko srities optinei reflektometrijai, projektavimo metodika, leidžianti pasiekti optimalų dinaminį diapazoną apskaičiuojant fotodiodo stiprinimo koeficientą, grįžtamojo ryšio varžą ir stiprintuvo įėjimo tranzistoriaus fizinius matmenis.
3. Taikant 0,35 μm KMOP technologiją, suprojektuotas ir ištirtas integrinis diferencinis pereinamos varžos stiprintuvas su grįžtamojo ryšio varža nuo 20 kΩ iki 800 kΩ, ir 107 MHz maksimalia dažnių juosta, leidžiantis gauti geresnę reflektometro skiriamąją gebą ir sumažintą nejautrumo zoną iki 2 metrų.

Praktinė vertė

Sukurta optinio imtuvo projektavimo metodika yra taikoma tobulinant esamus ir kuriant naujus komercinius laiko srities optinius reflektometrus. Suprojektuoto diferencinio pereinamos varžos stiprintuvo su kintama apkrovos varža integrinis grandynas yra skirtas plataus iki 42 dB dinaminio diapazono ir mažos, iki 2 metrų nejautrumo zonos, naujos kartos laiko srities optinių reflektometrų gamybai.

Ginamieji teiginiai

1. OTDR optinio imtuvo apibendrintas triukšmų modelis įvertina didžiausią įtaką turinčius triukšmų šaltinius ir taikytinas laiko srities optinių reflektometrų

tyrimuose, siekiant nustatyti grįžtamojo ryšio varžos, griūtinio fotodiodo dauginimo faktoriaus ir įėjimo tranzistoriaus fizinius matmenis, kuriems esant gaunamas optimalus dinaminis diapazonas.

2. Pasiūlyta optinio imtuvo projektavimo metodika leidžia gauti optimalų reflektometro dinaminį diapazoną, kuriam esant gaunamas 5% sumažintas signalo triukšmo santykis, o matuojamų signalų diapazonas 0,1–10 MHz dažnių juostų diapazone praplečiamas 1,4–2,1 kartų, kai optinis imtuvas suprojektuotas iš diskrečiųjų komponentų.

3. Integrinis 0,35 μm KMOP technologijos diferencinis pereinamos varžos stiprintuvas su kintama grįžtamojo ryšio varža nuo 20 kΩ iki 800 kΩ turi praplatintą dažnių juostą nuo 100 kHz iki 107 MHz, ir 2 metrų optinio reflektometro nejautrumo zoną, esant 15 mW vartojamajai galiai.

Darbo apimtis

Disertaciją sudaro įvadas, keturi skyriai, rezultatų apibendrinimas ir vienas priedas. Darbo apimtis yra 113 puslapiai, neįskaitant priedų, tekste panaudotos 74 numeruotos formulės, 54 paveikslai ir 13 lentelių. Rašant disertaciją buvo panaudoti 103 literatūros šaltiniai.

Pirmajame skyriuje atlikta reflektometrinių sistemų ir jų matavimo principų analizė, aptari sąryšiai tarp pagrindinių parametrų. Skyriaus pabaigoje formuluojamos išvados ir tikslinami disertacijos uždaviniai.

Antrajame skyriuje analizuojama optinio imtuvo struktūra, sudaromas jo triukšmų modelis, nustatomi pagrindinių parametrų optimalumo kriterijai bei pasiūloma projektavimo metodika.

Trečiajame skyriuje siekiant patikrinti triukšmų modelį atliekamas optinio imtuvo iš diskrečiųjų elementų projektavimas ir tyrimas. Analizuojami ir lyginami skaičiavimo bei matavimo rezultatai.

Ketvirtajame skyriuje atliekamas pereinamos varžos stiprintuvo projektavimas ir tyrimas ir skaičiuojami bei analizuojami jo pagrindu sudaryto optinio imtuvo parametrai.

Bendrosios išvados

1. Disertacijoje atlikta optinių reflektometrų struktūrų ir jų pagrindinių charakteristikų analizė. Daroma išvada, kad laiko srities optiniai reflektometrai yra plačiausiai naudojami optinių linijų parametrams matuoti. Suformuluota OR tobulinimo kryptis – reflektometro optinio imtuvo dinaminio diapazono optimizavimas, matuojamų signalų diapazono platinimas ir nejautrumo zonos mažinimas.

2. Darbe išnagrinėta optinio imtuvo struktūra ir pagrindiniai triukšmų šaltiniai, turintys didžiausią įtaką reflektometriniams matavimams ir duotos

analitinės išraiškos šiems triukšmams skaičiuoti bei aptartas jų minimizavimas. Sudarytas apibendrintas triukšmų modelis, kuriuo remiantis buvo atliktas tolimesnis optinių imtuvų tyrimas.

3. Sukurta OI projektavimo metodika, kuri leidžia apskaičiuoti optimalius griūtinio fotodiodo dauginimo faktorių, pereinamosios varžos stiprintuvo grįžtamojo ryšio varžą ir įėjimo tranzistoriaus fizinius matmenis, kuriems esant gaunamas optimalus dinaminis diapazonas. Jis yra 5% mažesnis už maksimalų dinaminį diapazoną, tačiau gaunama iki kelių kartų sumažinta grįžtamo ryšio varžos vertė ir atitinkamai praplečiamas matuojamų signalų diapazonas.
4. Suprojektuotas optinis imtuvas iš diskrečiųjų elementų ir atliktas eksperimentinis tyrimas. Iš skaičiavimo ir matavimo rezultatų palyginimo nustatyta, kad jų skirtumų vidurkis apie 0,1 dB, todėl projektavimo metodika tinka optimaliai grįžtamo ryšio varžai skaičiuoti, kuriai esant gaunamas optimalus dinaminis diapazonas.
5. Siekiant praplėsti dažnių juostą iki 100 MHz, atliktas diferencinio pereinamos varžos stiprintuvo integrinio grandyno projektavimas, modeliavimas ir tyrimas 0,1–100 MHz dažnių juostuose su kintama nuo 20–800 kΩ grįžtamojo ryšio varža ir 107 MHz maksimalia pralaidos juosta taikant 0,35 µm KMOP technologiją. Suprojektuotas stiprintuvas leidžia iki 2 metrų sumažinti laiko srities optinio reflektometro nejautrumo zoną, kai matavimams naudojama 3 ns lazerio impulso trukmė ir -50 dB atspindžio koeficientas.

Trumpos žinios apie autorių

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TIME DOMAIN OPTICAL REFLECTOMETER SYSTEMS INVESTIGATION

Summary of Doctoral Dissertation
Technological Sciences, Electrical and Electronic Engineering (01T)

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LAIKO SRITIES OPTINIŲ REFLEKTOMETRINIŲ SISTEMŲ TYRIMAS

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