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¹A NOVEL VARIABLE BIT-RATE BANDWIDTH LIMITER FOR OPTICAL TRANSMISSION SYSTEM

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ABSTRACT

We propose and experimentally demonstrate a novel variable bit-rate limiter (BRL) for ASK optical transmission systems. The BRL operates on the sampling principle with an optical switch inserted anywhere between the terminals in the fiber link. To facilitate the design of the BRL, a theoretical model of bit-error-rate (BER) for the proposed BRL is developed, and shows good agreement with the experimental data.

Keywords: Bit rate limiter, Optical Sampling, switch, eye-diagram, BER

1. INTRODUCTION

The ever-increasing demand in bandwidth resources could result in the proliferation of leasing dark fibers from the telecommunication operators to various enterprises, such as the central banks to their remote sites. The enormous bandwidth available in the fiber could very well be segmented under different tariff schemes. Because of the privacy issues, direct tapping of data through any means is strictly prohibited. It is therefore of great economic interests for the bandwidth providers to ensure that the users are not transmitting at data rates much higher than is allowed by their subscription fee. Such assurance should be enforced; otherwise, the bandwidth of one user will spread into bandwidth allocated to other users in a wavelength division multiplexed (WDM) system. In such situation, crosstalk and thus penalty will be observed at the users' end. The effect is especially detrimental in a dense WDM (DWDM) system as the channel bit rate is increased to a value comparable to the channel spacing (100GHz at present). For instance, many manufacturers plan to bring out 10 Gbit/s product, and MCI has declared its intention to build a backbone with 32 wavelengths and 40 Gb/s per channel[1]. Therefore, devices or schemes, which impose limits on transmission data rates, or bit rate limiter (BRL), are needed.

Since direct tapping of transmitting data is prohibited by laws due to privacy issues, the bit rate limiting scheme must be non-intrusive in nature. Also, any such scheme or device should be robust, low cost, and should consume little power. Furthermore, it should be bit rate variable such that future upscale in bandwidth demand does not require extensive overhaul of the system.

Previously, two BRL schemes with operations based on interferometric principles were proposed for OOK systems [2-3]. The scheme in [2] is based on a fiber loop such that delayed optical pulses, say ONE bit, will be added to the original pulse. Transmission rate higher than that allowed by the fiber delay will generate delay pulses smearing into next ONE bit separated by ZERO, effectively adding erroneous bits in the transmitting sequence. The scheme in [3] was based on a Mach Zehnder interferometer with similar results on the transmitting data sequence. Neither of these schemes, however, offers a variable bit rate capability and their operations are restricted to low bit rates due to substantial polarization-dependent phase-induced intensity noise. The phased-induced intensity noise is practically difficult, if not impossible, to be removed, as the polarization (not the bit level) of the incoming data is randomized. In this paper, we will demonstrate and analyze a simple and powerful BRL scheme, which is non-intrusive in nature and requires little maintenance.

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The paper is discussed as follows. Following the illustration of the proposed scheme in section 2, we will describe the theory of operation in section 3. Analyses will be given for systems modulated with on-off keying (OOK). Section 4 will describe the experiments and results. Discussion on the design of the BRL is given in section 5 and is followed by the conclusion in section 6.

2. PROPOSED SCHEME

Figure 1 shows our proposed BRL scheme using sampling as the operation principle [4]. The scheme requires an optical switch or intensity modulator be inserted anywhere between the end terminals in a point-to-point fiber link, or prior to the wavelength combiner in a WDM system. We assume that the switch is modulated independently of the transmitting data, as there should be no connection with the terminals at either end.

The optical switch is modulated at a switching rate f_s , which is much faster than the data transmission rate f_d . For digital data transmission, the ONE and ZERO bits will be sliced. The high-frequency variations of the time-slices can be eliminated by the low-pass filtering at the receiver if $f_s > f_d$, leaving only the envelope of the signal. The ONE and ZERO bits will appear as full bits with negligible distortion. We are, of course, assuming the receiver bandwidth is optimized with the data transmission such that the receiver bandwidth is close to the said transmission bandwidth of the system. As f_s approaches f_d , the time-slice of period $1/f_s$ becomes increasingly comparable to the signal period $1/f_d$. This can cause the voltage, at the bit decision time, swings below the threshold value for the ONE bits, resulting in an increase in bit error rate. For $f_s < f_d$, the ONE bits can be eliminated entirely by the slicing of the modulator, resulting in a BER floor in the system. Thus, by properly choosing the switching rate f_s , the data rate is effectively clamped. To change the bit rate limit, one can simply alter f_s applied to the switch.

In this paper, we only consider OOK modulation, in which the switch causes no effect on the ZERO bits. When other modulation formats are chosen, the results will be different. The NRZ and RZ formats will also perform differently. The effects when different modulation formats are used will be discussed elsewhere.

3. THEORY

In principle, the theory of BRL operation using sampling technique is based on the classic bit-error rate theory with modifications to include the bit slicing at the modulator. We include the dominant effect of inter-symbol interference in evaluating the bit error rate.

3.1. Probability of Errors

While the noises are stochastic in nature, the variations in the bit level are deterministic arising from the inter-symbol interference. It is our intention to develop a model that best resembles the error detection process of a bit-error-rate tester (BERT). From the BERT, a fixed length of PRBS is generated recursively to modulate the laser transmitter, which gives an output signal $S_o(t)$. The output is fed into a switch. Assuming a sinusoidal input bias with a frequency f_s and random phase ϕ , the normalized modulation function of the switch is expressed as

$$g(t) = 1 + \sin[0.5\pi \sin(2\pi f_s t + \phi)] \quad (1)$$

where we assume the applied sinusoidal signal has an exact amplitude to switch the modulator output from its minimum to its adjacent maximum. The combined signals from the modulation with the transmitting signal is then

$$S(t) = k[S_o(t)g(t)] * h(t) \quad (2)$$

where $h(t)$ is the transfer function of the low pass filter, and k is a constant factor derived from the fiber attenuation α , fiber coupling loss \mathcal{L} , and the responsivity η of the detector, i.e., $k = \alpha\mathcal{L}\eta$.

In our model, a long data sequence (10^4 bits) is generated from a 2^{10} -1 NRZ PRBS. The initial phase of the switch modulation signal, ϕ , is randomly generated for each run. The amplitudes of received ONE bits and ZERO bits are then sampled and grouped into $a_{11}, a_{12}, a_{13}, \dots$ and $a_{01}, a_{02}, a_{03}, \dots$, respectively. The sample point is chosen at the maximum eye-opening of the eye diagram from the simulation. A histogram of N bins can then be constructed, as shown in Fig. 2, for the received ONE bits amplitude, with D_{1m} and A_{1m} representing the occurrence frequency and the mean value of the m^{th} bin, respectively. Similarly, a histogram for the ZERO bits can also be obtained. From the sampled amplitude of ONE bit, it is found experimentally that the histogram remains the same for different initial phase ϕ . Therefore, we can assume that A_{1m} , A_{0m} , D_{1m} , and D_{0m} are independent of ϕ . We can then write the probability of error for the ONE bit, P_{e1} , and the ZERO bit, P_{e0} , as

$$P_{e1} = \frac{1}{2U_1} \sum_{m=1}^N D_{1m} \cdot \text{erfc} \left(\frac{A_{1m} - v_{th}}{\sigma_{1m} \sqrt{2}} \right) \quad (1)$$

$$P_{e0} = \frac{1}{2U_0} \sum_{m=1}^N D_{0m} \cdot \text{erfc} \left(\frac{v_{th} - A_{0m}}{\sigma_{0m} \sqrt{2}} \right) \quad (2)$$

where $U_1 = \sum D_{1m}$ and $U_0 = \sum D_{0m}$, and v_{th} is the decision threshold given by $2v_{th} = \langle a_{0k} \rangle + \langle a_{1k} \rangle$. In these expressions, the noise variances σ_{1m} and σ_{0m} for the respective ONE and ZERO bits are

$$\sigma_{1m} = \sqrt{\sigma_i^2 + \sigma_{s1m}^2 + \sigma_{RIN1m}^2} \quad (3)$$

$$\sigma_{0m} = \sqrt{\sigma_i^2 + \sigma_{s0m}^2 + \sigma_{RIN0m}^2} \quad (4)$$

where σ_i^2 is the thermal noise, σ_{s1m}^2 (σ_{s0m}^2) is the shot noise for the ONE (ZERO) bits, and σ_{RIN1m}^2 (σ_{RIN0m}^2) is the relative intensity noise for the ONE (ZERO) bits. Assuming the occurrence probability is identical for the ONE bit and the ZERO bit, the BER can be written as

$$BER = \frac{1}{2} (P_{e1} + P_{e0}) = \frac{1}{4U_0} \sum_{m=1}^N \left[D_{1m} \cdot \text{erfc} \left(\frac{A_{1m} - v_{th}}{\sigma_{1m} \sqrt{2}} \right) + D_{0m} \cdot \text{erfc} \left(\frac{v_{th} - A_{0m}}{\sigma_{0m} \sqrt{2}} \right) \right] \quad (5)$$

The values used in simulation are listed in Table 1. The values of the noise variance listed in Table 1 are calculated by the following three equations [5] and the unit of all of them are Ampere square (A^2).

$$\text{Thermal noise:} \quad \sigma_i^2 = \frac{4k_b T B r^2}{R} \quad (6)$$

$$\text{Shot noise:} \quad \sigma_s^2 = 2e \langle I \rangle B r \quad (7)$$

$$\text{Relative intensity noise:} \quad \sigma_{RIN}^2 = 10^{\frac{RIN}{10}} \langle I \rangle^2 B \quad (8)$$

$\langle I \rangle$ represents the average current at the receiver output, and other values of the parameters used in calculating the noises are listed in Table 2.

The system penalty derived from the simulation results is shown in Fig. 3. The result agrees very well with the experimental data, showing the validity of the model.

4. EXPERIMENTS

The experimental set up is shown in Fig. 1. Bit error rate measurements were performed using a 2^{10} -1 NRZ PRBS data modulated at 600 Mbps. The data signal is applied to a DFB laser transmitter ($\lambda = 1555$ nm) but with the switch modulated sinusoidally from $f_s = 550$ MHz to 2 GHz. The system penalty at $BER = 10^{-9}$ is represented by the dots shown in Fig. 3. The suitable switching rate for limiting data rate to 600 Mbps is 800 MHz, if the data rate is claimed to be limited when the system penalty is 1 dB. Then, we fixed the switching rate at 800 MHz and measured the BER curves for data rates

increasing from 200 Mbps to 718 Mbps (Fig. 4). Derived from Fig. 4, the characteristics of the bit-rate limiter is shown clearly in Fig. 5 with a sharp increase in power penalty (for BER at 10^{-9}) as f_d approaches f_s . Experiments on other bit rates were also performed and similar results and conclusions were obtained.

5. DISCUSSION

5.1. The transfer function of the BRL

Ideally, the system penalty imposed by the BRL should be negligible at data rates equal to or below the predetermined bit rate, and then surges afterwards. For an electronic low-pass filter, the transfer function is mainly characterized by several parameters, including its 3-dB pass-band frequency, the steepness of the transfer function in the transition band, the stop-band amplitude, and the ripple in pass-band and stop-band. The transfer function (system penalty versus data rate) of a BRL can be characterized similarly. The first is its *1-dB data rate*, $f_{1\text{-dB}}$, at which the system penalty is 1 dB. The second is the *cut-off data rate*, $f_{\text{cut-off}}$, at which the system penalty is, for instance, 5 dB. The third is the *steepness* of the line connecting these two points. Let us take Fig. 5 as an example. The data rate at system penalty = 1 dB is 600 Mbps, the cut-off data rate is ~700 Mbps and the slope joining these two point is ~0.04 dB/Mbps. By examining these parameters, we can estimate the resultant penalty if a particular data is used in a system installed with a BRL.

5.2. The relationship between the system penalty and the ratio f_d/f_s

Here, we study the behavior of the system penalty in terms of the ratio of the data rate to the switching rate by simulations. Using our numerical model, we simulate the BER curves for data rates 250 Mbps, 400 Mbps and 800 Mbps at the same RF filter bandwidth to data rate ratio (B/f_d) 0.75. The system penalty is derived from the three BER curves. Similarly, system penalties for the ratio 0.80, 0.85 and 0.9 are also obtained. All the system penalties are plotted against f_d/f_s in Fig. 6. Consider the three curves for the same ratio 0.75, they overlap each other all the way up. It is because the system penalty introduced by the switch and the filter is the same for the same f_d/f_s . When the data rate is low, all the curves overlap each other. The reason is that the switching rate is much higher than the RF filter bandwidth, so the slicing details are eliminated by the RF low-pass filter no matter what the ratio is. However, when f_d/f_s increases, i.e. the switching rate decreases, the band width of the filter becomes a critical factor to determined the BER. Thus, the curves with different ratio separate gradually. In the nutshell, there exists a relation between the system penalty and the ratio of data rate to switching rate, for the same filter bandwidth to data rate ratio.

6. CONCLUSIONS

We have demonstrated a simple yet powerful variable BRL, which consists of an optical switch inserted anywhere along the optical fiber link. The bit rate limiting effect was demonstrated at $f_d = 600$ Mbps and similar results were obtained for other data rates. Also, Both experiments and simulations for designing the switching rate were performed and good agreement was shown. Hence, the scheme is effective and the simulation model for determined the suitable switching rate is valid. Also, the BRL can be characterized as a low-pass filter and there exists a relation between the system penalty and the ratio of data rate to switching rate, for the same filter bandwidth to data rate ratio.

7. ACKNOWLEDGE

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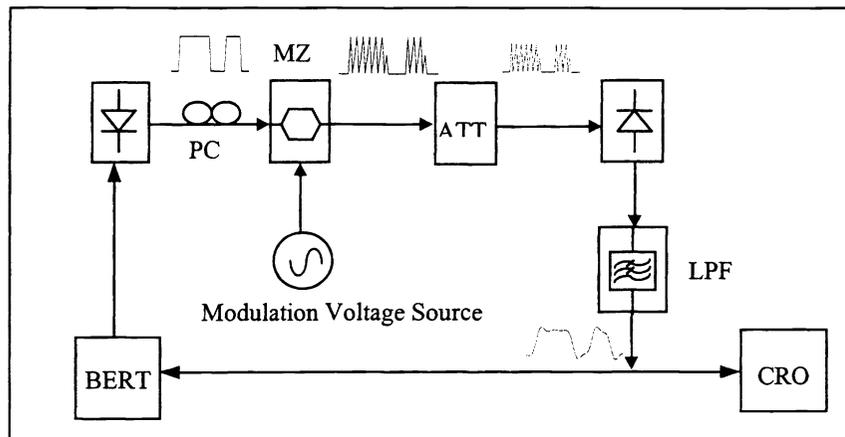


Fig. 1 Experimental set up (PC = polarization controller, MZ = Mach-Zehnder switch (UTP APE MZM-1.5-8-T-1-1) with insertion loss= 3 dB and extinction ratio= 26 dB, ATT = optical attenuator, LPF = low pass filter, CRO = oscilloscope, BERT=bit error rate tester and data pattern generator).

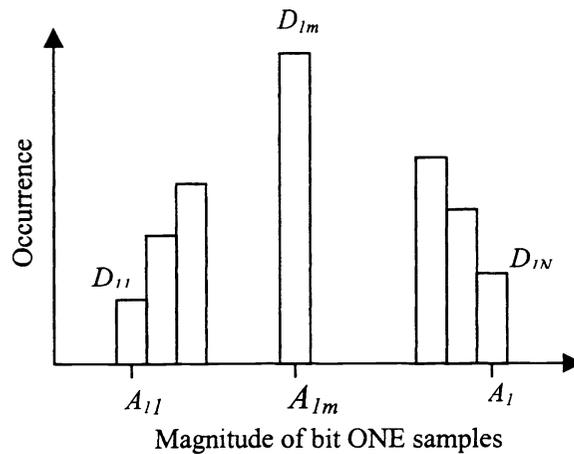


Fig. 2 A histogram formed by the bit ONE samples.

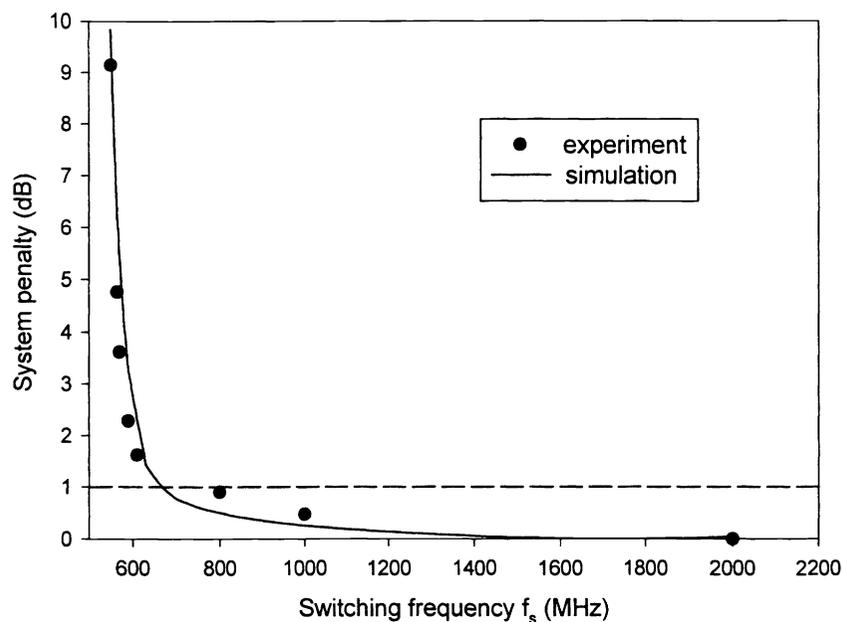


Fig. 3 The line represents the system penalty derived from the simulation. The dots represent the system penalty derived from experimental results. In both case, the data rate is 600 Mbps (2^{10} -1 PRBS, NRZ) and the 3-dB bandwidth of the RF filter is 455 MHz.

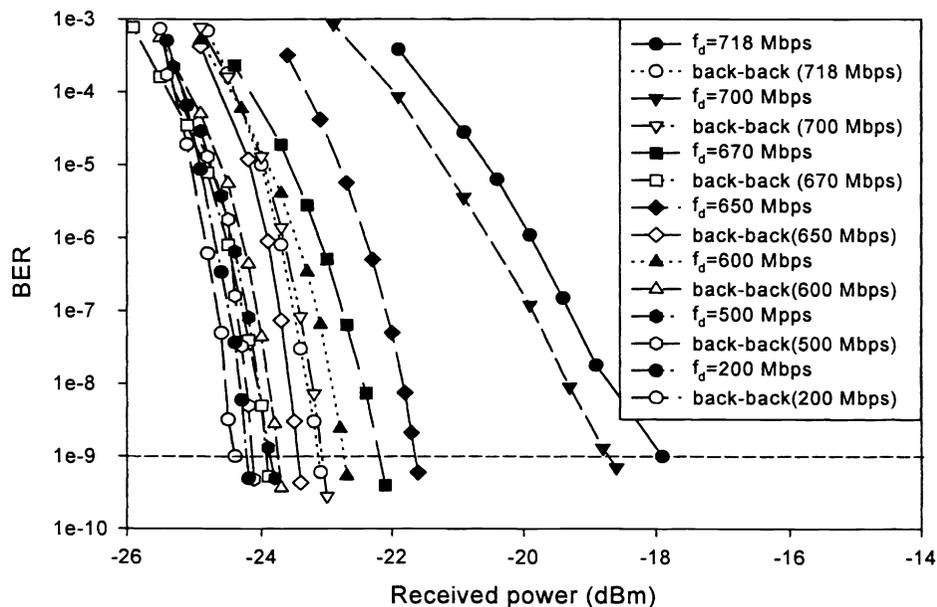


Fig. 4 Experimental results. BER performance for switching rate $f_s = 800$ MHz with data rate f_d varied from 200 Mbps to 718 Mbps (2^{10} -1 PRBS, NRZ). The 3-dB bandwidth of the RF filter used is 455 MHz.

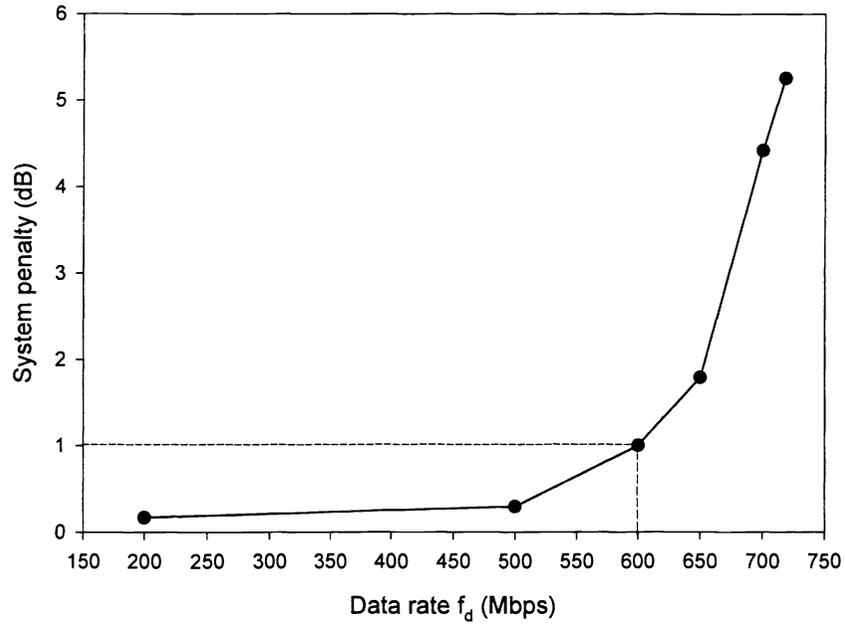


Fig. 5 Experimental results. System penalty derived from Fig. 4

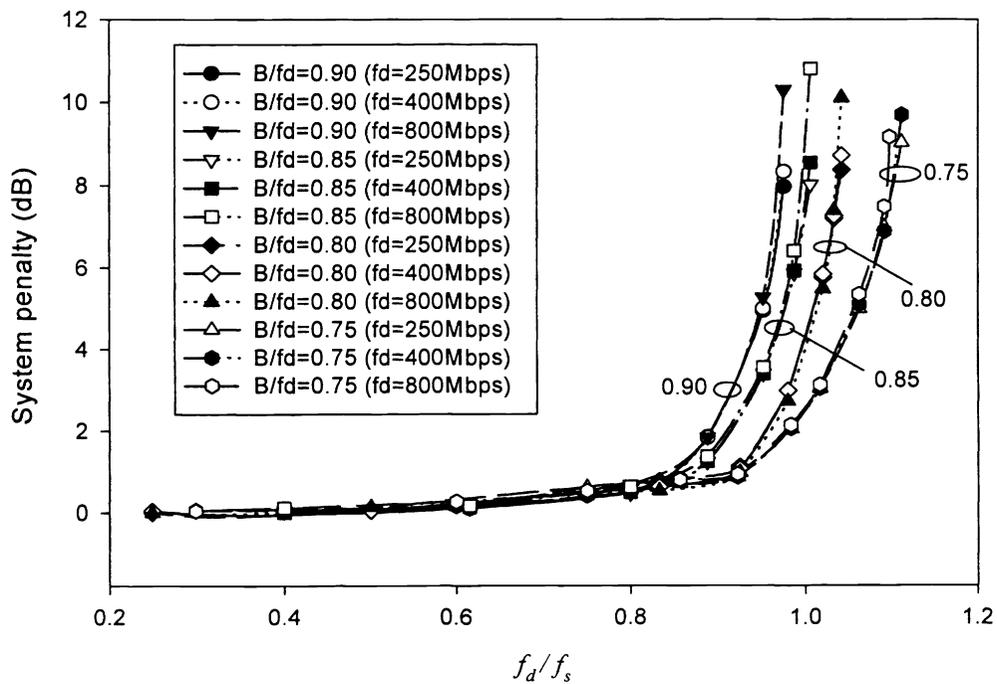


Fig. 6 The system penalty for different ratio of receiver bandwidth to data rate (B/f_d): 0.9, 0.85, 0.8 and 0.75.

Variables and function in numerical analysis model	Values in program
$S_0(t)$	NRZ 2 ¹⁰ -1 PBRs data sequence with length 10000, and each bit symbol is represented by 18 samples
$g(t)$	$1 + \sin(1.2 \sin(2\pi f_s t + \phi) 2\pi/4.8)$
K	Varies as needed
R	31.6 A/W
$h(t)$	Butterworth filter with bandwidth 455 MHz and 9 th order
σ_i^2	$1.5 \times 10^{-4} \text{ (mA)}^2$
σ_{s0m}^2	$4.60 \times 10^{-6} (A_{0m} - \min(a_{0k})) \text{ (mA)}^2$
σ_{s1m}^2	$4.60 \times 10^{-6} (A_{1m} - \min(a_{1k})) \text{ (mA)}^2$
σ_{RIN0m}^2	$9.08 (A_{0m} - \min(a_{0k}))^2 \text{ (mA)}^2$
σ_{RIN1m}^2	$9.08 (A_{1m} - \min(a_{1k}))^2 \text{ (mA)}^2$

Table 1 Values of the parameters and functions in the numerical analysis model.

Parameters	Values
k_b (Boltzmann's constant)	$1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$
T (temperature)	298 °K
B (filter 3-dB-bandwidth)	455 MHz
R (resistance)	50 Ω
e (electron charge)	$1.60 \times 10^{-19} \text{ C}$
RIN	-127 dB/Hz

Table 2 The values used to calculate the noises.