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A device and method for generating a polybinary signal

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Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
15 February 2018 (15.02.2018)

WIPO | PCT

(10) International Publication Number
WO 2018/028924 A1

(51) International Patent Classification:
H04L 25/49 (2006.01)

(21) International Application Number:
PCT/EP2017/067745

(22) International Filing Date:
13 July 2017 (13.07.2017)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
16184044.2 12 August 2016 (12.08.2016) EP

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

(54) Title: A DEVICE AND METHOD FOR GENERATING A POLYBINARY SIGNAL

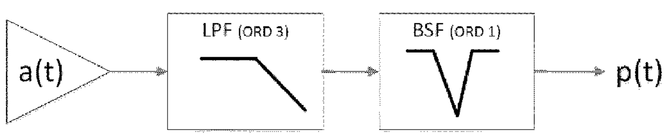

Fig. 1

(57) Abstract: The present disclosure relates to a method for generating an L-level polybinary signal, comprising the steps of: providing a baseband signal with a spectrum defined by a predefined frequency period, f_p; filtering the baseband signal using a low-pass filter having a pre-defined cut-off frequency, $f_{c\text{-}o}$, and a preefined polynomial order, n, whereby the L-polybinary signal is generated; filtering the L-polybinary signal before or after it is generated, with at least one band-stop filter having a pre-defined center frequency, f_c, and a pre-defined bandwidth, Δ, thereby isolating f_p of the baseband signal.

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A device and method for generating a polybinary signal

Field of invention

The present invention relates to tele and/or data communication, in particular a method and a device for generating a polybinary signal used in tele and/or data communication.

Background of invention

Polybinary modulation formats were proposed originally in the 60s by A. Lender to overcome the bandwidth limitation of copper-based transmission media. Polybinary modulation formats are also known as partial response modulation formats. Polybinary modulations provide an increment of the number of levels of the original digital signal by introducing controlled amounts of inter symbol interference (ISI). The simplest polybinary modulation, known as duobinary, correlates a symbol with its predecessor; for example if the original signal is binary (two levels), the duobinary modulated signal will present three levels.

Moreover Lender patented the standard technique for m-levels polybinary modulation and demodulation; this standard technique, also referred as digital, includes digital electronic components such as shift registers, flip-flops, and arithmetic adder and modulo two gates.

Furthermore in the 70s, L. I. Bluestein designed a universal polybinary modem based on Lender digital technique.

Variants of the 5 and 7 polybinary signals can be generated analogically by applying a low-pass filter (LPF) to the binary or multilevel input signal. The LPF affects the rise and fall time of each symbol according to the previous ones; this relation between symbols can be used to shape an input of a non-return-to-zero (NRZ) signal into an output duobinary or 4-level polybinary signal.

Given the bit rate, *Br* [Gbps] of the input NRZ signal, each symbol period or duration is given by $T=1/Br$ [s] and the spectrum of each symbol is a sync function of period $f_p=1/T$. In the time domain, the sampling points of a signal are usually chosen in the middle of symbol period, where the signal is flat, if jitter and other impairments are neglected. At the receiver, sampling points can be used as decision points for assigning values to the detected symbols. Unfortunately the three or four sampling points of the output analog polybinary signal are significantly deteriorated by the filter; by the other hand the transition points, located at the beginning and the end of each symbol period, are less affected by the filter. By shifting the decision points from the sampling to the transition ones, the output signal becomes a 5 or 7-level partial response or polybinary variant from a duobinary or 4-level polybinary respectively. The main advantage of this analogical method is that it doesn't require any synchronization of the input signal; however the output multilevel signal presents higher distortion respect their digital generated counterparts.

The LPFs are usually Bessel filters because of their maximally flat group delay characteristic. The current state-of-the-art of the analog polybinary modulation formats includes an experimental demonstration of a 5-levels polybinary from a binary input signal and a 7-levels duobinary from a 4-pulse amplitude modulated (4 PAM) input signal. Simulation results have shown that an ideal Bessel LPF can modulate a binary signal into 7-levels and 9-levels polybinary by properly selecting the order and cut-off frequency of the filter. However, one problem with the current state-of-the art is that if the modulator applies the digital technique, it requires synchronization with the input signal otherwise if it applies the analog technique, it introduces signal distortion, which limits the performance of the system. Accordingly, there is a need for a more efficient way to generate a polybinary signal.

Summary of invention

The present disclosure relates in a first aspect to efficiently generating a polybinary signal. In order to overcome the problems with the current state-of-the art, a method for generating an L-level polybinary signal is provided. The method comprises the steps of: providing a baseband signal with a spectrum defined by a pre-defined frequency period, f_P; filtering the baseband signal using a low-pass filter, the low-pass filter having a pre-defined cut-off frequency, $f_{c\text{-}o}$, and a pre-defined polynomial order, n. The low-pass filter thereby provides attenuation for each symbol of the baseband signal dependent on the previous symbol(s). In this manner, the L-polybinary signal is generated. The method further comprises the step of filtering the L-polybinary signal, before or after it is generated, with at least one band-stop filter having a pre-defined center frequency, f_c, and a pre-defined bandwidth, *Δ,* thereby isolating f_P of the baseband signal.

As can be understood from the herein disclosed method, the idea is to replicate the spectrum of the generated polybinary signal using a low-pass filter in cascade with one or more band-stop filters.

The low-pass filter introduces the relation between symbols in the baseband signal as with the standard analog method.

A baseband signal or low-pass signal is a signal that has spectral magnitude that is nonzero only for frequencies in the proximity of the origin and negligible elsewhere (for example, a sound waveform can be considered as a baseband signal, whereas a radio signal or any other modulated signal is not). Accordingly, a baseband signal may also be an electric signal and/or a digital signal.

The at least one band-stop filter is used for reproducing the frequency period of the generated polybinary signal. As described in relation to the herein disclosed method, the at least one band-stop filter is configured for isolating f_P of the baseband signal. The isolation of f_P may in most embodiments be a focused isolation, defined by the characteristics of the band-stop filter. By applying a band stop filter as here defined, the frequency period of the baseband signal, is prevented from being spread outside the pass-band of the low-pass filter. In comparison to the standard analogue method, where only a single low-pass filter is used to generate the polybinary signal, a higher order filter would need to be used to achieve the same isolation of f_P because the isolation provided by the filter is spread over the entire rejected band.

As a consequence, the order of the low-pass filter, *n,* according to the present invention, may then be relaxed. That is, in comparison to a standard analogue method, the selectivity requirement of *n* may be much lower than what is required by conventional methods with a single low-pass filter.

Several advantages are provided by relaxing the order *n*. This will be described in the following.

The present disclosure provides two alternative schemes of polybinary modulation to the current state-of-the art. Regardless of the scheme, the present invention provides for a method for generating a polybinary signal without the need of synchronizing the modulator to the input signal, thereby overcoming one of the problems with the traditional methods of generating a polybinary signal.

The first scheme, which in the following is referred to as “scheme A” uses one band-stop filter, only. The second scheme, which in the following is referred to as “scheme B” uses more than one band-stop filters.

Because of the linearity of analog filters, both schemes are symmetric and the position of the low-pass filter and the at least one band-stop filter does not affect the modulation performance. The two may be in cascade. Accordingly, the order of the LPF and the BSF can be such that the LPF is before the BSF, or the BSF can be before the LPF. As long as the two types of filters are cascaded, a polybinary signal can be made without the need of synchronizing the modulator to the input signal.

Scheme A is used only for generating the variant of 5 and 7 levels polybinary signals as the standard analog technique, whereas scheme B can be used to generate any L-level polybinary signal as the digital technique. Thus, in contrast to scheme A and the current state-of-the art, scheme B provides an analog solution for generating all desirable L-level polybinary signals.

Scheme A and B are both improvements of the traditional analog scheme with a Bessel LPF in that the signals are generated more easily and provide higher spectral efficiency than the current state-of-the art technique. Further, scheme A and B also reduces signal distortion in comparison to the current state-of-the-art. The effects as described here are provided by the band-stop filter according to the invention.

In one embodiment, the present method is operable in a communication system, such as a telecommunication system.

In a second aspect of the invention, there is provided a device for generating an L-level polybinary signal from a baseband signal with a spectrum defined by a pre-defined frequency period, f_P, comprising: a low-pass filter configured for filtering the baseband signal, the low-pass filter having a pre-defined cut-off frequency, $f_{c\text{-}o}$, and a pre-defined polynomial order, *n.* The low-pass filter thereby provides attenuation for each symbol of the baseband signal dependent on the previous symbol(s). In this manner, the *L*-polybinary signal is generated. and the devive further comprises at least one band-stop filter configured for filtering the *L*-polybinary signal, before or after it is generated, the at least one band-stop filter having a pre-defined center frequency, f_c, and a pre-defined bandwidth, *Δ,* such that it isolates f_P of the baseband signal.

As here disclosed, the present device is able to be manufactured with low cost elements, thereby providing a low cost solution for generating an *L*-level polybinary signal.

In one embodiment, the present device is configured for being integrated into a communication system, such as a telecommunication system.

Thus, in a further aspect the invention relates to a telecommunication system integrating the method and device as here disclosed.

Description of drawings

Fig. 1 shows an embodiment of method according to the present invention, represented by a schematic, here referred to as scheme A.

Fig. 2 shows an embodiment of method according to the present invention, represented by a schematic, here referred to as scheme B.

Fig. 3 shows the normalized spectrum of the input PRBS binary signal (red), of a digitally generated 4-level polybinary signal (green) and the transfer function of scheme A designed for 7-level polybinary variant. Both signals are at 10 Gbps.

Fig. 4 shows the normalized eye diagram of a 4-levels polybinary signal at 10 Gbps for a signal generated by the digital technique.

Fig. 5 shows the eye diagram of a 7-levels polybinary signal at 10 Gbps and modulated by scheme A.

Fig. 6 shows the normalized spectrum of input PRBS binary signal (red), of a digitally generated 7-level polybinary signal (green) and the transfer function of scheme B designed for 7-level polybinary. Both signals are at 10 Gbps.

Fig. 7 shows the normalized eye diagram of a 7-levels polybinary signal at 10 Gbps, for a signal generated by the method according to the present invention, here referred to as scheme B.

Fig. 8 shows the eye diagram of a 7-levels polybinary signal at 10 Gbps and generated by scheme B.

Fig. 9 shows a lumped elements implementation example of scheme A for 5-levels polybinary at 10 Gbps.

Fig. 10 shows a lumped elements implementation example of scheme A for 7-levels polybinary at 10 Gbps

Fig. 11 shows the S21 curves and eye diagrams of scheme A for 5-levels and 7-levels polybinary signals.

Fig. 12 shows a lumped elements implementation example of scheme B for 5-levels polybinary at 10 Gbps.

Fig. 13 shows a lumped elements implementation example of scheme B for 7-levels polybinary at 10 Gbps.

Fig. 14 shows a lumped elements implementation example of scheme B for 9-levels polybinary at 10 Gbps.

Fig. 15 shows the S21 curves and eye diagrams of scheme B for 5-levels, 7-levels and 9-levels polybinary signals

Fig. 16 shows the eye diagrams of 5 and 7-levels polybinary signals at 10 Gbps and generated with the standard analogue technique and scheme A.

Fig. 17 shows the eye diagrams of 4, 5, 6, 7, 8, 9, 10 and 11-levels polybinary signals at 10 Gbps and generated with scheme B.

Fig. 18 shows eye diagrams of 5 and 7-levels polybinary signals generated with the standard analogue technique and scheme A as in **Fig. 16**. The parameters are here shown as a function of the frequency period, f_P,of the input signal.

Fig. 19 shows **e**ye diagrams of 4, 5, 6, 7, 8, 9, 10 and 11-levels polybinary signals generated with scheme B as in **Fig. 17**. The parameters are here shown as a function of the frequency period, f_P,of the input signal.

Fig. 20 shows eye diagrams of NRZ, duobinary and 4-level polybinary signals generated by digital electronics. The grey dots are the sampling points and the red points the transition ones.

Detailed description of the invention

The present disclosure relates in a first aspect to a method for generating a polybinary signal, and in a second aspect to a device for generating a polybinary signal. Both the method and the device are related to the idea of using one or more band-stop filters. In the following, features that relate to both the method and the device are described.

Low-pass filter

In one embodiment of the invention, the low-pass filter is a Bessel filter. A Bessel filter has a phase lag that is directly proportional to the frequency. In other words, a Bessel filter is a linear phase filter. A linear phase filter can be approximated using the so-called Thompson approximation as this approximation has a phase function that approximates a linear-phase function. Thus, a Bessel filter is also called a Thompson filter. In a Bessel filter, or a Thompson filter, Bessel polynomials are used in obtaining the filter coefficients. The polynomial of order L and coefficients c_n that also defines the polybinary signal may be expressed as:

$$p_k = \sum_{n=0}^{L-1} \mathrm{C}_n a_{k-n},$$

where the input signal with a_k is correlated to the previous input signal.

In a preferred embodiment of the present invention, the low-pass filter is applied analogically to said signal. This may for example be done using an analogue device. Applying the filter analogically has the advantage that synchronization, or rather correlation, of the modulation signal and the input signal is not required.

In another preferred embodiment of the present invention, the low-pass filter is implemented by an analogue device and/or an integrated circuit such as an ASIC. By applying an analogue filtering, it may be said that the filtering is performed and defined in the frequency domain.

It is well-known that polybinary signals may be generated analogically, for example using an analogue device. Generating polybinary signals analogically provides for low complexity filtering, real time processing and great flexibility of an analogue device. Nevertheless, it is also well-known that the state-of-the art analogue polybinary signal generation is achieved on the cost of signal distortion, in particular for high level polybinary signal generation, since signal distortion increases with the number of levels. However, because the present invention uses one or more band-stop filters, it is possible to decrease the order of the low-pass filters, thereby decreasing the signal distortion. Accordingly, by the present invention, low signal distortion is possible to be achieved with an analogue device for generating polybinary signals.

Filter transfer functions are normally derived as low-pass functions. Frequency transformations are then used to transform the low-pass functions into either high-pass, band-pass, or band-reject transfer functions. For a low-pass filter, the cutoff frequency of the filter is denoted $f_{c\text{-}o}$. Depending on the type of filter, it is not necessarily the −3 dB cutoff frequency. However, in embodiments of the present invention, the cut-off frequency is the -3 dB cut-off frequency.

In a preferred embodiment, the cut-off frequency of the low-pass filter is less than 25% of the frequency period, more preferably less than 20% or less than 16% than the frequency period. In other embodiments, the cut-off frequency of the low-pass filter is less than 11% of the frequency period.

Band-stop filter

In one embodiment of the present invention, the band-stop filter is a Bessel filter of order 1. As previously described, because the present invention uses one or more band-stop filters, it is possible to decrease the order of the low-pass filters, thereby decreasing the signal distortion.

In one embodiment of the present invention, the band-stop filter is applied analogically to said signal. This may for example be done using an analogue device.

In a second embodiment of the present invention, the band-stop filter is applied in a frequency domain of said signal. This may for example be done using an analogue device. Applying the band-stop filter analogically provides the possibility for a purely analogue device, whereby a low cost device is able to be obtained.

In a preferred embodiment of the present invention, the bandwidth of the band-stop filter is identical to or less than 10% of the frequency period, such as less than 9% of the frequency period, such as less than 8% of the frequency period, such as less than 7% of the frequency period, such as less than 6% of the frequency period, such as less than 5% of the frequency period. Stated differently, the bandwidth of band-stop filter may be between 5% and 10% of the frequency period.

In embodiments of the present invention, the bandwidth as described herein is the -3 dB bandwidth.

Input and output signal

In one embodiment of the invention, the baseband signal comprises a random binary sequence. More particular, the baseband signal may be a pseudo random binary sequence (PRBS), where the input signal with a_k as previously defined, is comprised of zeroes and ones. The zeroes and ones are examples of symbols in a digital baseband signal. On and off states in an electric signal may be considered symbols of an electric baseband signal.

In another embodiment of the invention, the baseband signal is transmitted and/or coded as a non-return-to-zero (NRZ) signal. Given the bit rate, *Br* [Gbps], of the input NRZ signal, each symbol period or duration is given by $T=1/Br$ [s] and the spectrum of each symbol is a sync function of period $f_P=1/T$.

S-parameters describe the input-output relationship between ports (or terminals) in an electrical system. For instance, if two ports, then S12 represents the power transferred from Port 2 to Port 1. S21 represents the power transferred from Port 1 to Port 2.

Scheme A

Scheme A relates to the method and/or device according to the present invention, where there is one band-stop filter, only. Using scheme A allows reducing the polynomial order of the low-pass-filter in comparison to the standard scheme where only a Bessel filter is used.

According to the present invention, using the A scheme, allows for example for generation of a 5-level polybinary signal using Bessel low-pass filter of order 3. The state-of-the art analogue method, where only a Bessel filter is used, i.e. without a band-stop filter, uses in comparison for the generation of a 5-level polybinary signal with a similar quality, a Bessel filter of order 4. Thus, in comparison to the state-of-the art analogue method, the present invention uses a Bessel filter one order less than what is conventionally required. Thereby is provided a method and device achieving a less distorted signal in comparison with the state-of the art method.

The order of the low-pass filter compared to the state-of-the art analog method is significantly reduced when generating a 7-level polybinary signal. Similarly to the 5-level polybinary signal, using the A scheme according to the present invention, allows for example also for generation of a 7-level polybinary signal using Bessel low-pass filter of order 3. The state-of-the art analogue method, where only a Bessel filter, i.e. without a band-stop filter uses in comparison for the generation of a 7-level polybinary signal with a similar quality, a Bessel filter of order 8. Thus, in comparison to the state-of-the art analogue method, the present invention uses a Bessel filter four orders less than what is conventionally required. Thereby is provided a method and device achieving a significantly less distorted signal in comparison with the state-of the art method.

In one embodiment of the present invention, the LPF is set to the same f_{c-0} of the standard scheme reported in the literature: 17-22% of f_P for 5 levels and 12-15% for 7-level polybinary.

In another embodiment of the present invention, the optimal bandwidth of the band-stop filter is independent of the L-level polybinary signal. Thus, scheme A provides for a very flexible design of for example an analogue device.
In a preferred embodiment of the present invention, the single band-stop filter has a center frequency, f_c, defined by $f_c=2f_P/(L-1)$. In particular f_c may equal $f_P/2$ for 5 and $f_P/3$ for 7-level polybinary, which correspond to the frequency period of generated 3 and 4-level polybinary signals respectively.Selecting the center frequency as here specified, may allow for optimal signal generation.

Scheme B

Scheme B relates to the method and/or device according to the present invention, where there is more than one band-stop filter. Accordingly, the at least one band-stop filter is a plurality of band-stop filters, defined as N, selected such that N band stop filters are in a cascade, wherein N is $N=L-2$.

Using scheme B allows for the low-pass-filter to be Bessel low-pass-filter with the pre-defined polynomial order of order 1. The LPF may have an optimal f_{c-0} ranging between 4-10% of f_P, depending on the number of levels L. As already disclosed, scheme B can be used to generate any L-level polybinary signal, and as now disclosed, by using a Bessel low-pass-filter with the pre-defined polynomial order of order 1. Thus, in comparison to scheme A, scheme B provides for a method and device achieving a significantly less distorted signal.

In a preferred embodiment of the present invention, the bandwidth of each of said band-stop filters is dependent of the L-level polybinary signal, and selected such that there is a linear relationship between L and Δ.

Each of said band-stop filters may be identified with an integer, k, such that the center frequency, f_c, of the k^{th} band-stop filter is located at a frequency defined by $f_c=kf_P/(L-1)$; where $f_{c1}=f_p/(L-1)$ is the frequency period of a generated L-level polybinary signal. Selecting the center frequency as here specified, may allow for optimal signal generation.

Device

As has already been disclosed, the device may be an analogue device.

In one embodiment of the present invention, the device is a printed circuit board, wherein the circuit board comprises: an input port configured for being connected to the baseband signal; and an output port configured for being connected to a transmitting medium.

According to the device as disclosed herein, the device may be able to operate with scheme A or scheme B. More particular, the device may be configured to perform the method according the first aspect of the invention.

In scheme A, the circuit board may further comprise a maximum of 5 lumped elements, wherein the lumped elements are 3 capacitors and 2 inductors or 2 capacitors and 3 inductors.

In scheme B, the circuit board may further comprise a maximum of $2N+1$ lumped elements, wherein the lumped elements are: $N+1$ capacitors and N inductors or N capacitors s and N+1 conductors.

Example 1 – Scheme A

Fig. 1 shows an embodiment of method according to the present invention, represented by a schematic, referred to scheme A. **Fig. 1** shows a method for generating an *L*-level polybinary signal. There is a baseband signal *a(t)* with a spectrum defined by a pre-defined frequency period, f_P. As the state-of-the art analog method, a Bessel LPF filters the high frequency components of the input signal; although in scheme A the presence of a single BSF provides a higher and more localized isolation at the frequency $f_P/2$ or $f_P/3$ (5 or 7 levels). The output signal, *p(t)*, is the *L*-level polybinary signal.

Example 2 – Scheme B

Fig. 2 shows an embodiment of method according to the present invention, represented by a schematic, referred to scheme B. **Fig. 2** shows a method for generating an *L*-level polybinary signal. There is a baseband signal *a(t)* with a spectrum defined by a pre-defined frequency period, f_P. A first order LPF provides attenuation to the high frequency components of the input signal; whereafter a plurality of BSFs provide a higher and more localized isolation at the frequencies $nf_P/(L-1)$, where n=1, 2,…, L-2. The output signal, $p(t)$, is the L-level polybinary signal.

Example 3 – Scheme A

Fig. 3 shows the normalized spectrum of the input PRBS binary signal at 10 Gbps (red). The blue curve is the S21 of scheme A designed for 7-levels polybinary modulation at 10 Gbps. When scheme A is applied to the input signal, the 7 levels output resembles the spectrum of a 4-levels polybinary signal, which is reported in green. The BSF of scheme A is centred at 3.33 GHz, which corresponds to the period of the 4-levels polybinary signal.

Example 4 – Scheme A

Fig. 4 shows the normalized eye diagram of a 4-levels polybinary signal at 10 Gbps and generated by the digital technique. The 4 levels at the sampling and the 7 levels at the transition points are marked in grey and red respectively.

Example 5 – Scheme A

Fig. 5 shows the eye diagram of a 7-levels polybinary signal at 10 Gbps and modulated by scheme A; the signal resembles a deteriorated 4-levels polybinary, where the 7 levels marked in orange correspond to its transition points.

Example 6 – Scheme B

Fig. 6 shows the normalized spectrum of input PRBS binary signal at 10 Gbps (red). The blue curve is the S21 of scheme B designed for 7-levels polybinary modulation at 10 Gbps. Moreover is shown in green the spectrum of a 7-levels polybinary signal modulated by the digital technique. When scheme B is applied to the input signal, the spectrum of the output signal resembles the 7-levels polybinary one.

Example 7 – Scheme B

Fig. 7 shows the normalized eye diagram of a 7-levels polybinary signal at 10 Gbps and generated by the digital technique; the 7 levels at the sampling points are marked in red.

Example 8 – Scheme B

Fig. 8 shows the eye diagram of a 7-levels polybinary signal at 10 Gbps and generated by scheme B; the 7 levels at the sampling points are marked in orange.

Example 9 – Device that implements scheme A

Fig. 9 shows a lumped elements implementation example of scheme A for 5-levels polybinary at 10 Gbps. The LPF includes two shunt capacitors and a series inductor, while the BPF is implemented as a shunt LC series.

Example 10 – Device that implements scheme A

Fig. 10 shows a lumped elements implementation example of scheme A for 7-levels polybinary at 10 Gbps. The LPF includes two shunt capacitors and a series inductor, while the BPF is implemented as a shunt LC series.

Example 11 – Scheme A

Fig. 11 shows the S21 curves and eye diagrams of scheme A for 5-levels (blue) and 7-levels (red) polybinary signals.

Example 12 – Device that implements scheme B

Fig. 12 shows a lumped elements implementation example of scheme B for 5-levels polybinary at 10 Gbps. The LPF is implemented as single shunt capacitors and the 3 BPFs in cascade as series LC parallel.

Example 13 – Device that implements scheme B

Fig. 13 shows a lumped elements implementation example of scheme B for 7-levels polybinary at 10 Gbps. The LPF is implemented as single shunt capacitors and the 5 BPFs in cascade as series LC parallel.

Example 14 – Device that implements scheme B

Fig. 14 shows a lumped elements implementation example of scheme B for 9-levels polybinary at 10 Gbps. The LPF is implemented as single shunt capacitors and the 7 BPFs in cascade as series LC parallel.

Example 15 – Scheme B

Fig. 15 shows the S21 curves and eye diagrams of scheme B for 5-levels (red), 7-levels (blue) and 9-levels (green) polybinary signals.

Example 16 – Scheme A in comparison to a method using a single LPF

Fig. 16 and Fig. 18 show the eye diagrams of 5 and 7-levels polybinary signals generated with the standard analogue technique and scheme A. The specifications of the LPF and BSF are reported in the third and fourth columns respectively.

Example 17 – Scheme B

Fig. 17 and Fig. 19 show in the second column the eye diagrams of 4, 5, 6, 7, 8, 9, 10 and 11-levels polybinary signals generated with scheme B. The specifications of the LPF and BSFs are reported in the third and fourth columns respectively.

Example 18 – Sampling points and transition points

Fig. 20 shows the eye diagrams of an NRZ, duobinary and 4-level polybinary signals generated by digital electronics. In the diagram the sampling point, in the middle of the symbol period, are marked with grey dots. Moreover the transition points, in the middle of the transition between adjacent symbols, are marked with red dots.

Claims

1. A method for generating an *L*-level polybinary signal, comprising the steps of:
   - providing a baseband signal with a spectrum defined by a pre-defined frequency period, f_P;
   - filtering the baseband signal using a low-pass filter, the low-pass filter having a pre-defined cut-off frequency, f_{c-o}, and a pre-defined polynomial order, *n,* thereby providing an attenuation for each symbol in the baseband signal dependent on the previous symbol(s) therein, whereby the *L*-polybinary signal is generated; and
   - filtering the *L*-polybinary signal, before or after it is generated, with at least one band-stop filter having a pre-defined center frequency, f_c, and a pre-defined bandwidth, Δ, thereby isolating f_P of the baseband signal.

2. The method according to claim 1, wherein the baseband signal comprises a random binary sequence.

3. The method according to any of the preceding claims, wherein the baseband signal is transmitted as a non-return-to-zero signal.

4. The method according to any of the preceding claims, wherein the low-pass filter is a Bessel filter.

5. The method according to any of the preceding claims, wherein the at least one band-stop filter is a Bessel filter of order 1.

6. The method according to any of the preceding claims, wherein the low-pass filter and/or the band-stop filter is applied analogically to the baseband signal.

7. The method according to any of the preceding claims, wherein the cut-off frequency and/or the bandwidth is/are the -3 dB cut-off frequency and/or the -3 dB bandwidth.

8. The method according to any of the preceding claims, wherein the bandwidth of the at least one band-stop filter is identical to or less than 10% of the frequency period, such as less than 9% of the frequency period, such as less than 8% of

the frequency period, such as less than 7% of the frequency period, such as less than 6% of the frequency period, such as less than 5% of the frequency period.

9. The method according to any of the preceding claims, wherein the bandwidth of the at least one band-stop filter is between 5% and 10% of the frequency period.

10. The method according to any of the claims 1-9, wherein the at least one band-stop filter is a single band-stop filter, and wherein the low-pass-filter is a Bessel low-pass filter with the pre-defined polynomial order of less than 4, such as an order of 3.

11. The method according to claim 10, wherein the cut-off frequency of the low-pass filter is less than 20% of the frequency period.

12. The method according to any of the claims 10-11, wherein the bandwidth of band-stop filter is independent of the L-level polybinary signal.

13. The method according to any of the claims 10-12, wherein the single band-stop filter has a center frequency, f_c, defined by $f_c=2f_P/(L-1)$.

14. The method according to any of the claims 1-9, wherein the at least one band-stop filter is a plurality of band-stop filters, defined as N, selected such that N band-stop filters are in a cascade, wherein N is $N=L-2$.

15. The method according to claim 14, wherein said low-pass-filter is a Bessel low-pass filter with the pre-defined polynomial order of order 1.

16. The method according to any of the claims 14-15, wherein the bandwidth of each of said band-stop filters is dependent of the L-level polybinary signal, and selected such that there is a linear relationship between L and Δ.

17. The method according to any of the claims 14-16, wherein each of said band-stop filters is identified with an integer, k, such that the center frequency, f_c, of

the k^{th} band-stop filter is located at a frequency defined by $f_c=kf_P/(L-1)$.

18. A device for generating an *L*-level polybinary signal from a baseband signal with a spectrum defined by a pre-defined frequency period, f_P, comprising:
    - a low-pass filter configured for filtering the baseband signal, the low-pass filter having a pre-defined cut-off frequency, f_{c-o}, and a pre-defined polynomial order, *n,* thereby providing an attenuation for each symbol of the baseband signal dependent on the previous symbol(s) therein, whereby the *L*-polybinary signal is generated; and
    - at least one band-stop filter configured for filtering the *L*-polybinary signal, before or after it is generated, the at least one band-stop filter having a pre-defined center frequency, f_c, and a pre-defined bandwidth, Δ, such that it isolates f_P of the baseband signal.

19. The device according to claim 18, wherein the low-pass filter is a Bessel filter.

20. The device according to any of the claims 18-19, wherein the at least one band-stop filter is a Bessel filter of order 1.

21. The device according to any of the claims 18-20, wherein the device is an analogue device and/or an integrated circuit, such as an ASIC.

22. The device according to any of the claims 18-21, wherein the bandwidth of the band-stop filter is identical or less than 10% of the frequency period, such as less than 9% of the frequency period, such as less than 8% of the frequency period, such as less than 7% of the frequency period, such as less than 6% of the frequency period, such as less than 5% of the frequency period.

23. The device according to any of the claims 18-22, wherein the bandwidth of band-stop filter is between 5% and 10% of the frequency period.

24. The device according to any of the claims 18-23, wherein the at least one band-stop filter is a single band-stop filter, and wherein the low-pass-filter is a Bessel low-pass filter with the pre-defined polynomial order of less than 4, such as an order of 3.

25. The device according to any of the claims 18-24, wherein the cut-off frequency of the low-pass filter is less than 20% of the frequency period.

26. The device according to any of the claims 18-25, wherein the bandwidth of band-stop filter is independent of the *L*-level polybinary signal.

27. The device according to any of the claims 18-26, wherein the single band-stop filter has a center frequency, f_c, defined by $f_c=2f_P/(L-1)$.

28. The device according to any of the claims 18-23, wherein the at least one band-stop filter is a plurality of band-stop filters, defined as *N*, selected such that *N* band stop filters are in a cascade, wherein *N* is $N=L-2$.

29. The device according to claims 28, wherein the low-pass-filter is a Bessel low-pass filter with the pre-defined polynomial order of order 1.

30. The device according to any of the claims 28-29, wherein the bandwidth of each of the band-stop filters is dependent of the *L*-level polybinary signal, and selected such that there is a linear relationship between *L* and *Δ*.

31. The device according to any of the claims 28-30, wherein each of the band-stop filters is identified with an integer, *k*, such that the center frequency, f_c, of the k^{th} band-stop filter is located at a frequency defined by $f_c=kf_P/(L-1)$.

32. The device according to any of the claims 18-31, wherein the device is a printed circuit board, wherein the circuit board comprises:
    - an input port configured for being connected to the baseband signal; and
    - an output port configured for being connected to a transmitting medium.

33. The device according to claim 32, wherein the circuit board further comprises a maximum of 5 lumped elements, wherein the lumped elements are 3 capacitors and 2 inductors or 2 capacitors and 3 inductors.

34. The device according to claim 32, wherein the circuit board further comprises a maximum of $2N+1$ lumped elements, wherein *N* corresponds to the plurality of

band-stop filters and wherein the lumped elements are: N+1 capacitors and N inductors or N capacitors s and N+1 inductors.

35. The device according to any of the claims 18-34, wherein the device is configured to perform the method according to any of the claims 1-18.

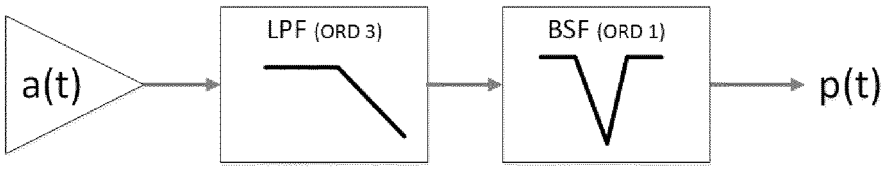

a(t)
LPF (ORD 3)
BSF (ORD 1)
p(t)

Fig. 1

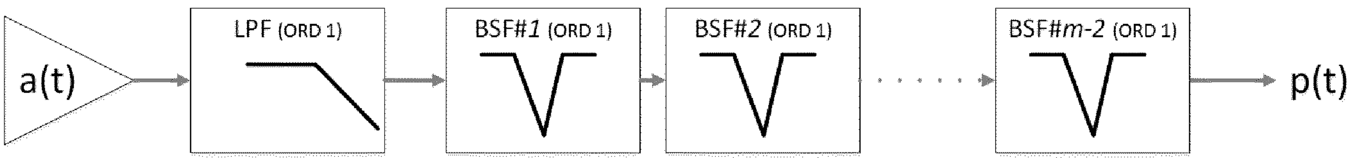

a(t)
LPF (ORD 1)
BSF#1 (ORD 1)
BSF#2 (ORD 1)
BSF#m-2 (ORD 1)
p(t)

Fig. 2

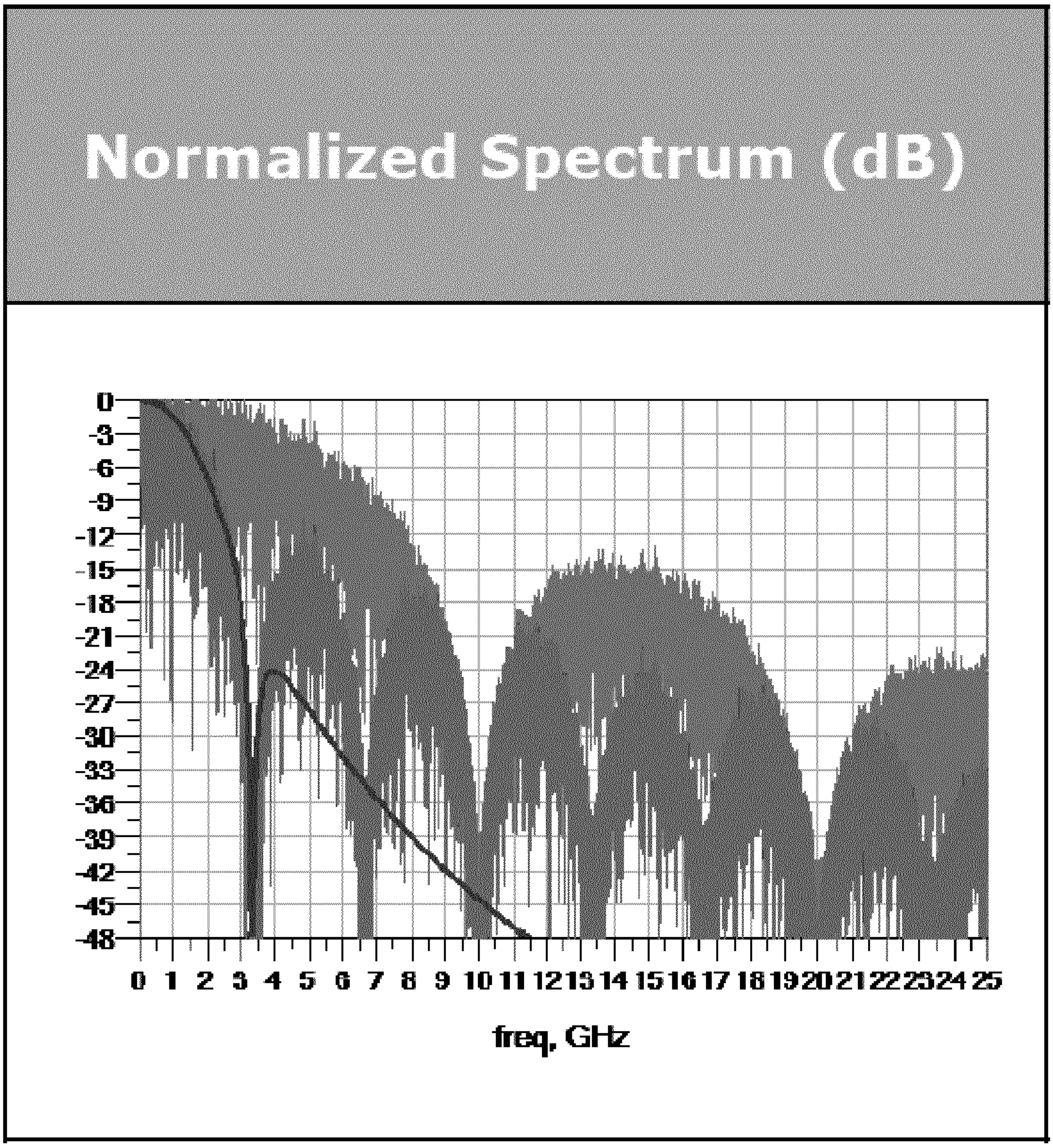

Normalized Spectrum (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-36
-39
-42
-45
-48
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
freq, GHz

Fig. 3

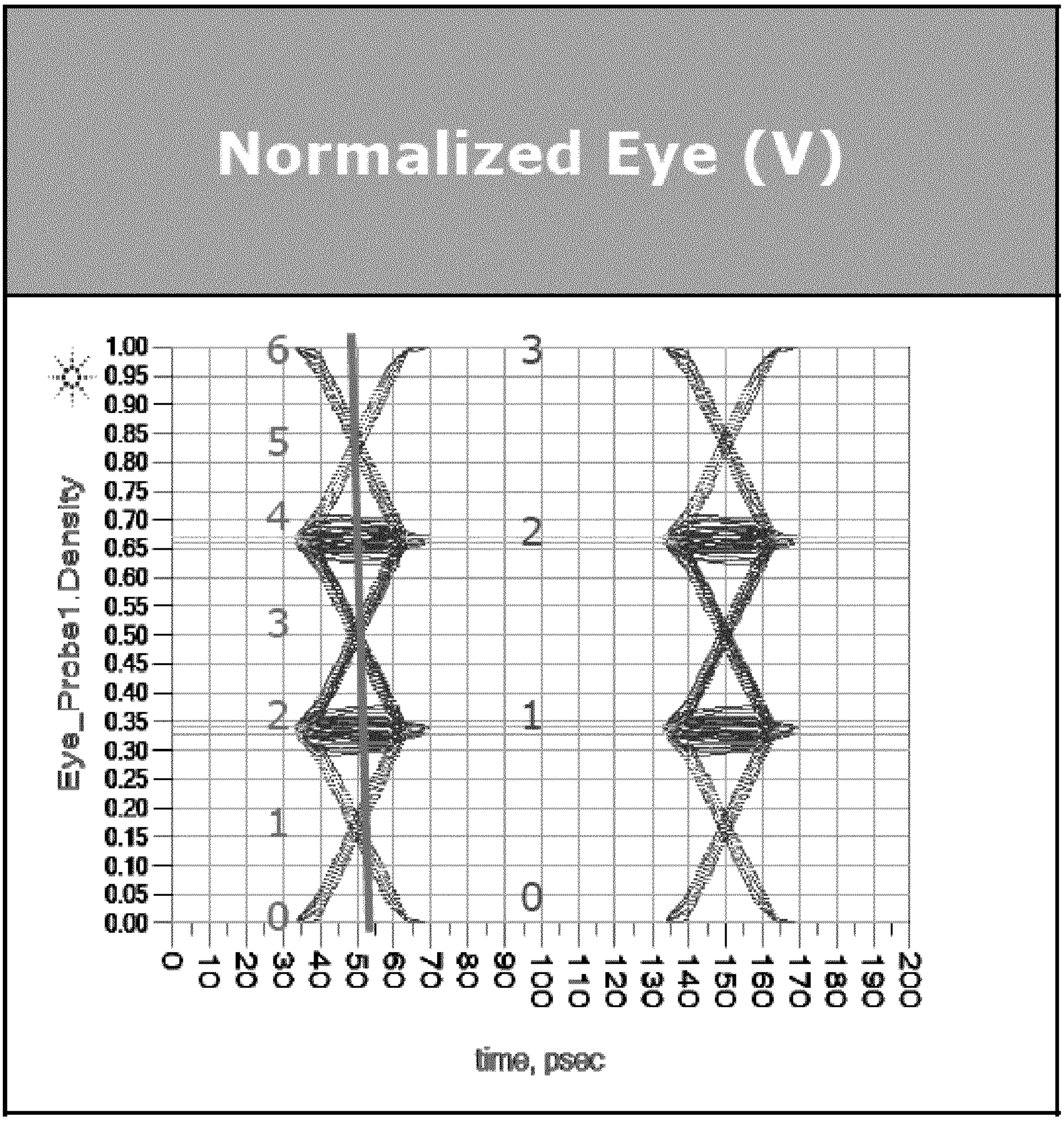

Normalized Eye (V)
Eye_Probe1.Density
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
6
5
4
3
2
1
0
3
2
1
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
time, psec

Fig. 4

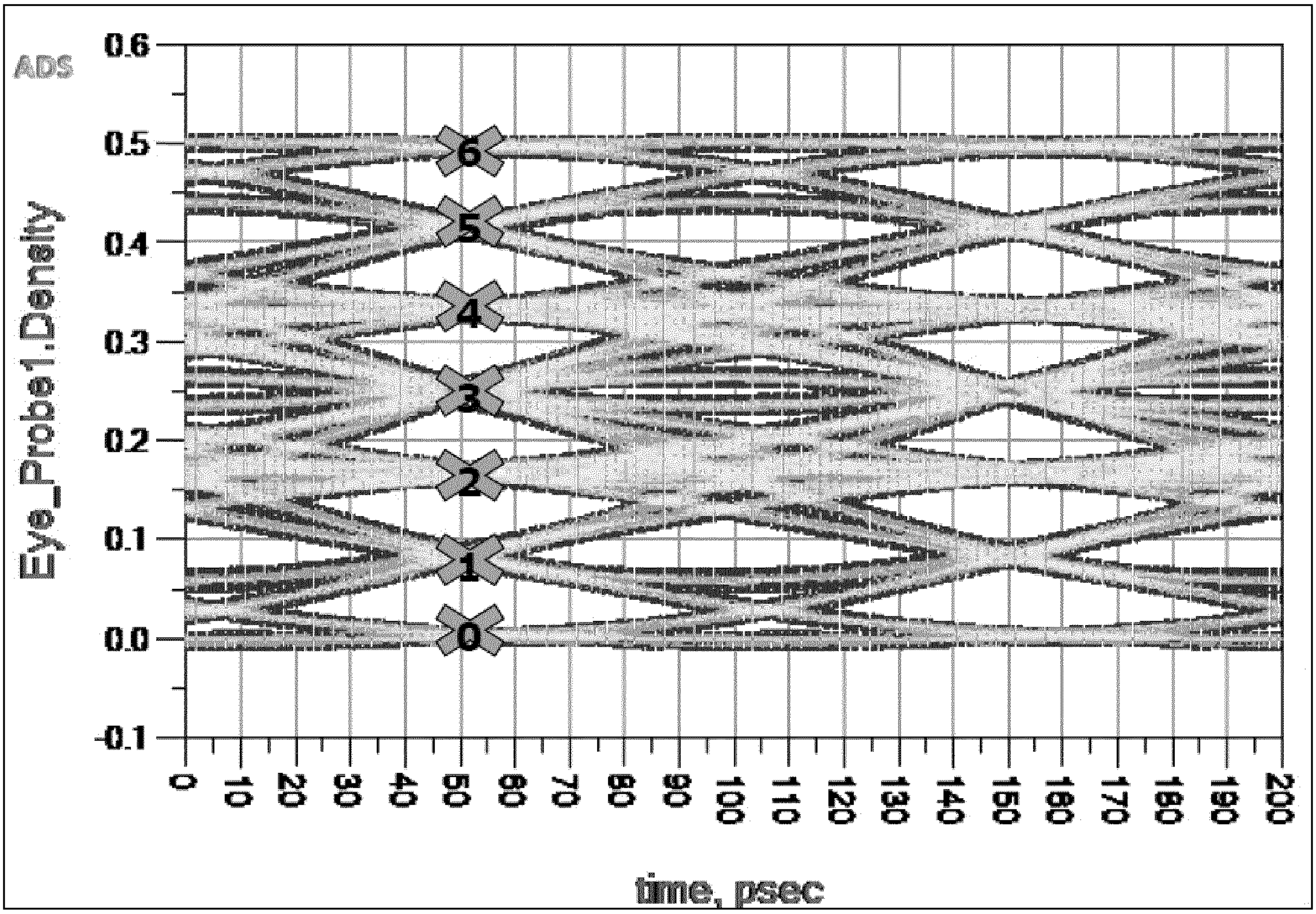

ADS
Eye_Probe1.Density
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
6
5
4
3
2
1
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
time, psec

Fig. 5

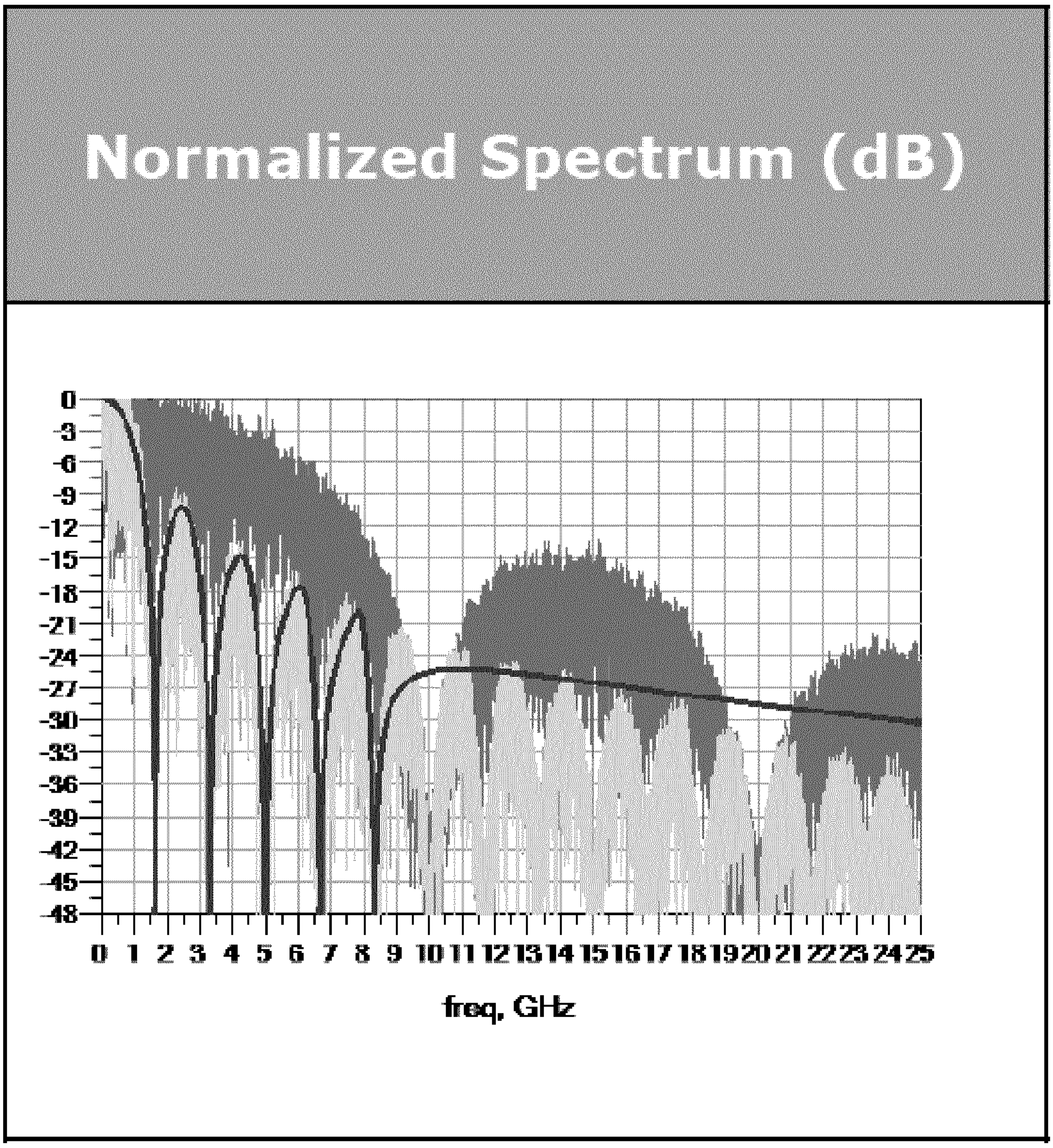

Normalized Spectrum (dB)
0
-3
-6
-9
-12
-15
-18
-21
-24
-27
-30
-33
-36
-39
-42
-45
-48
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
freq, GHz

Fig. 6

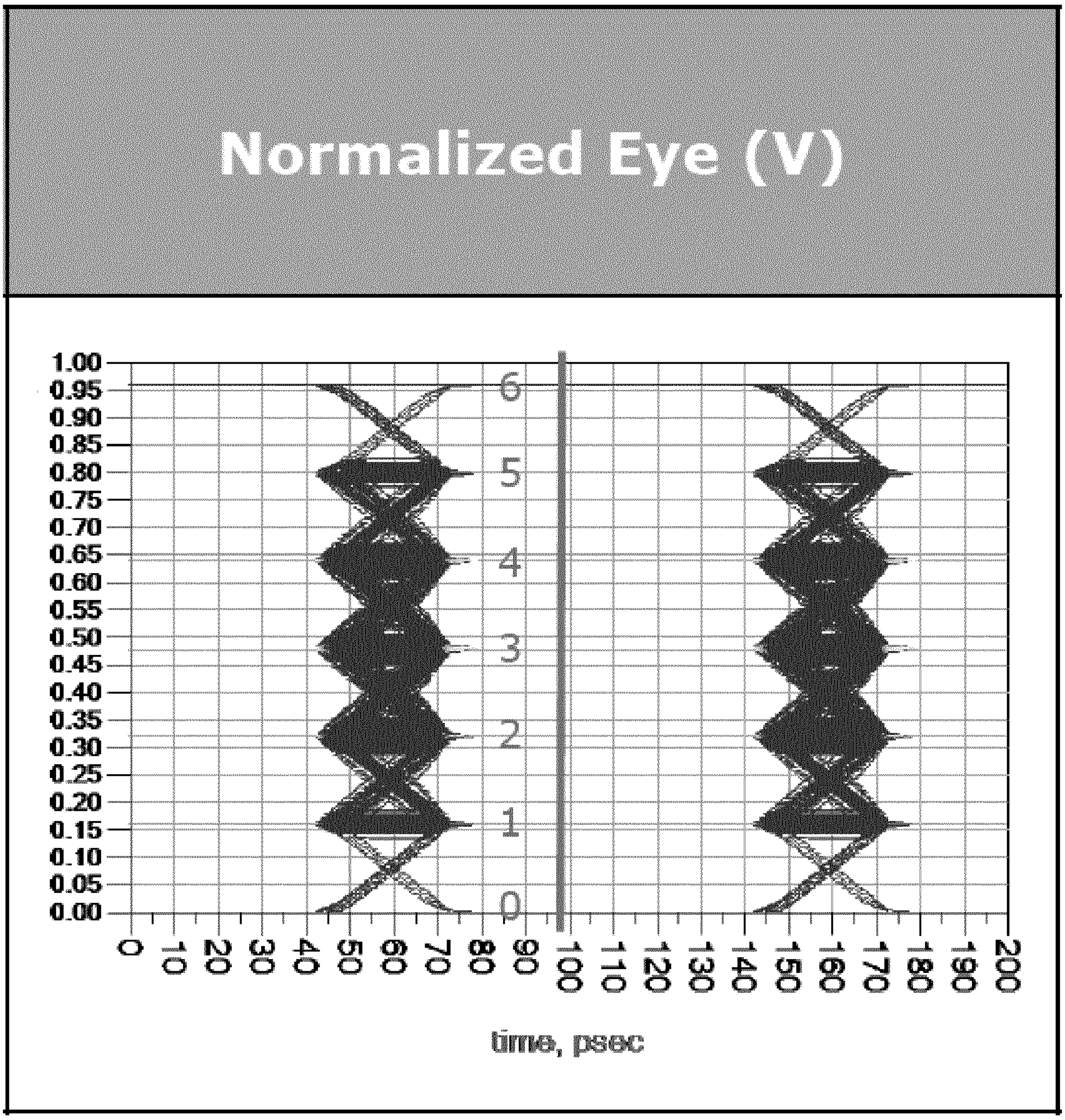

Normalized Eye (V)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
6
5
4
3
2
1
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
time, psec

Fig. 7

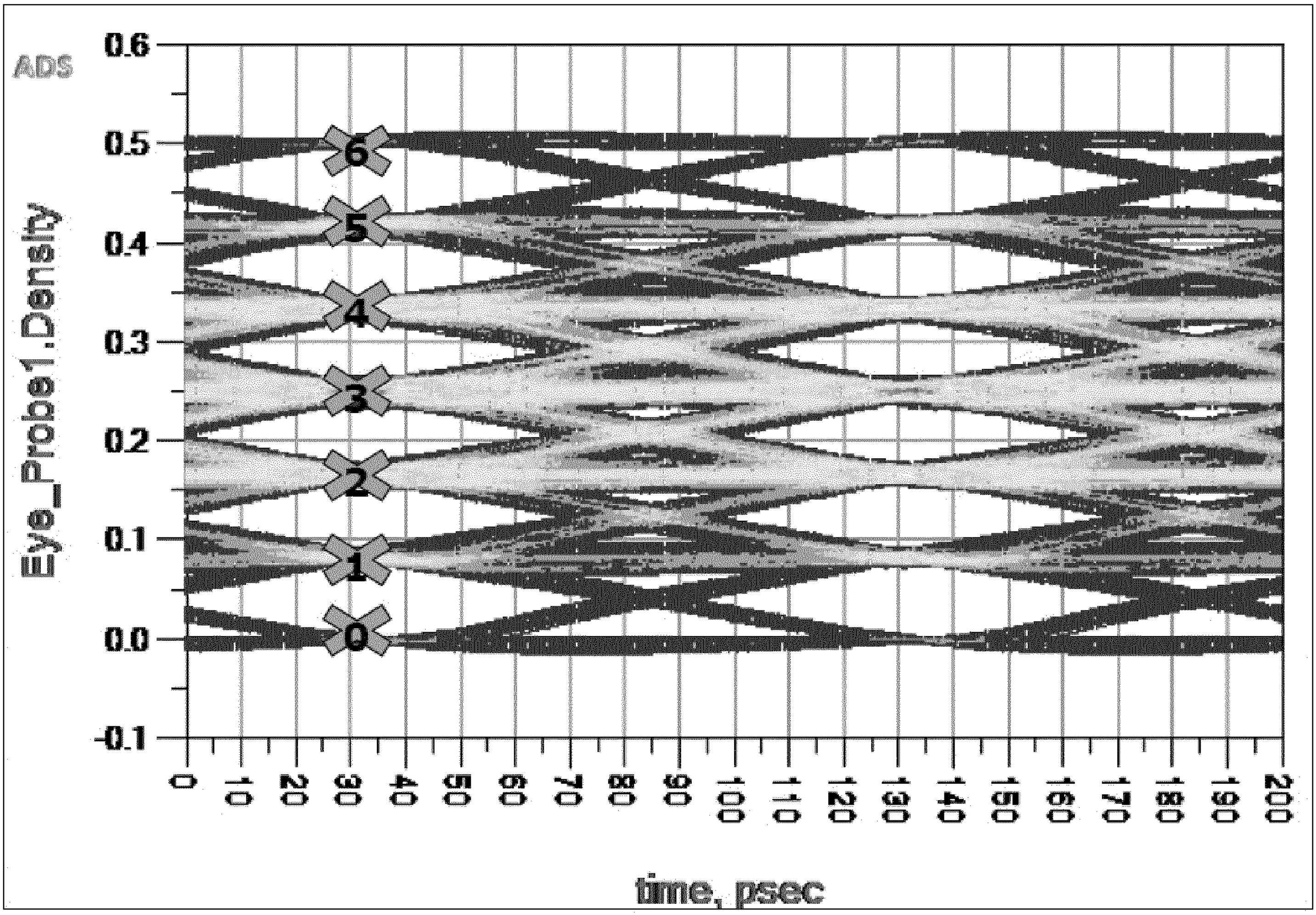

ADS
Eye_Probe1.Density
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
6
5
4
3
2
1
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
time, psec

Fig. 8

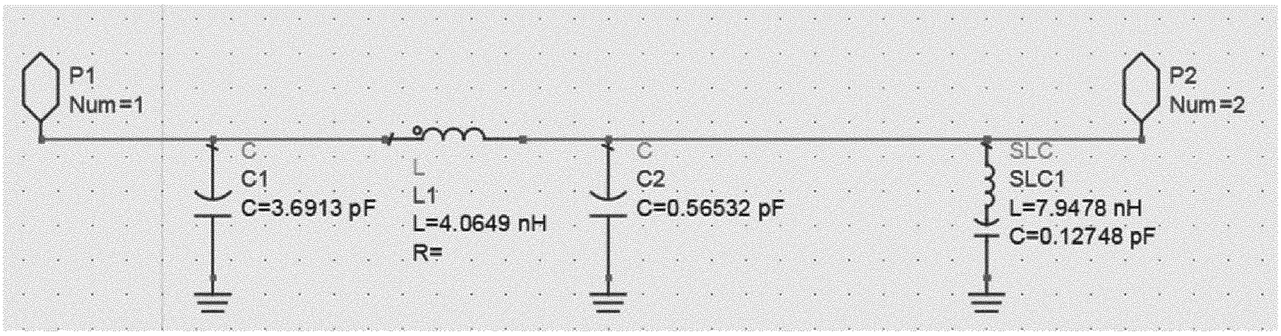

P1
Num=1
C
C1
C=3.6913 pF
L
L1
L=4.0649 nH
R=
C
C2
C=0.56532 pF
SLC
SLC1
L=7.9478 nH
C=0.12748 pF
P2
Num=2

Fig. 9

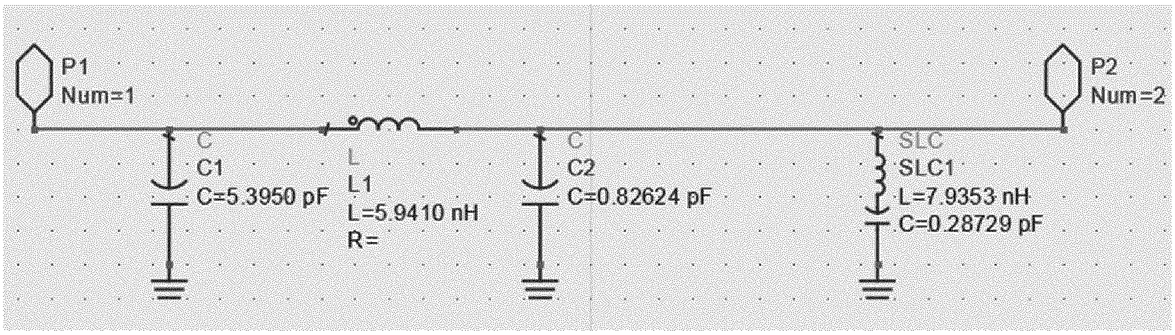

P1
Num=1
C
C1
C=5.3950 pF
L
L1
L=5.9410 nH
R=
C
C2
C=0.82624 pF
SLC
SLC1
L=7.9353 nH
C=0.28729 pF
P2
Num=2

Fig. 10

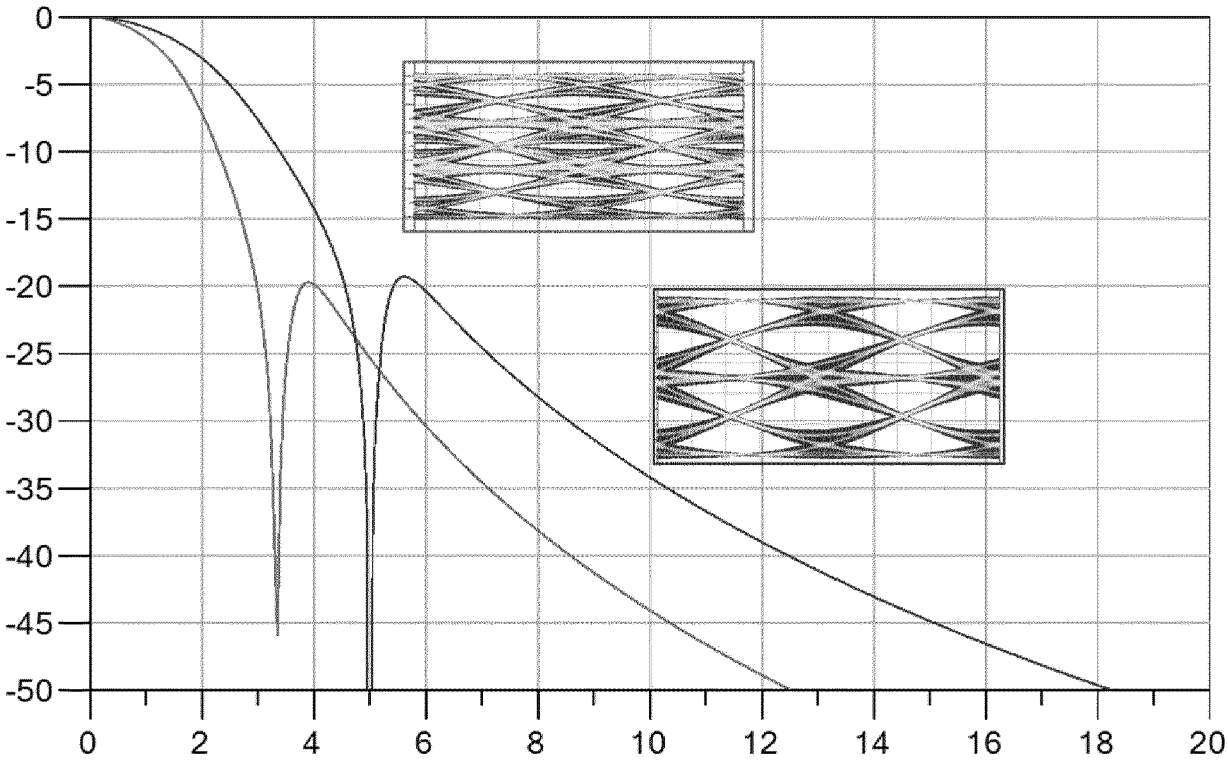


Fig. 11

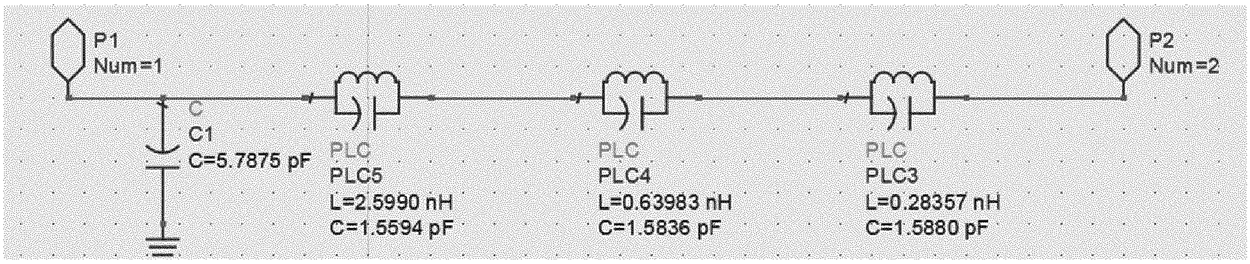


Fig. 12

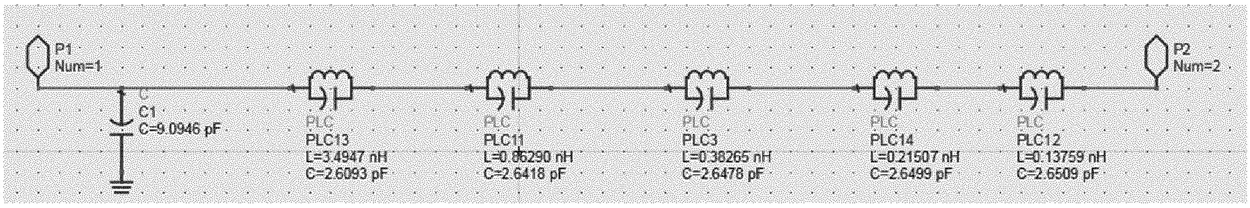


Fig. 13

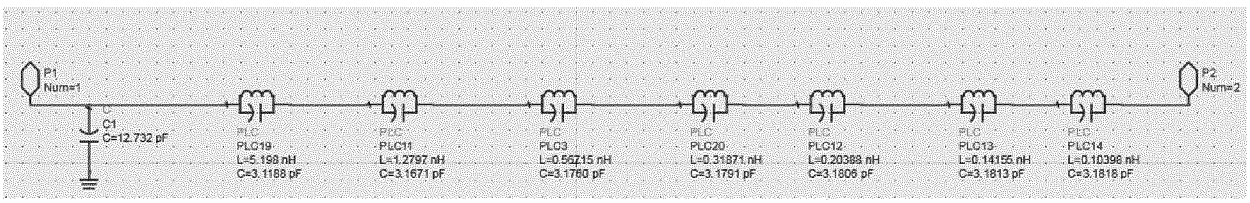


Fig. 14

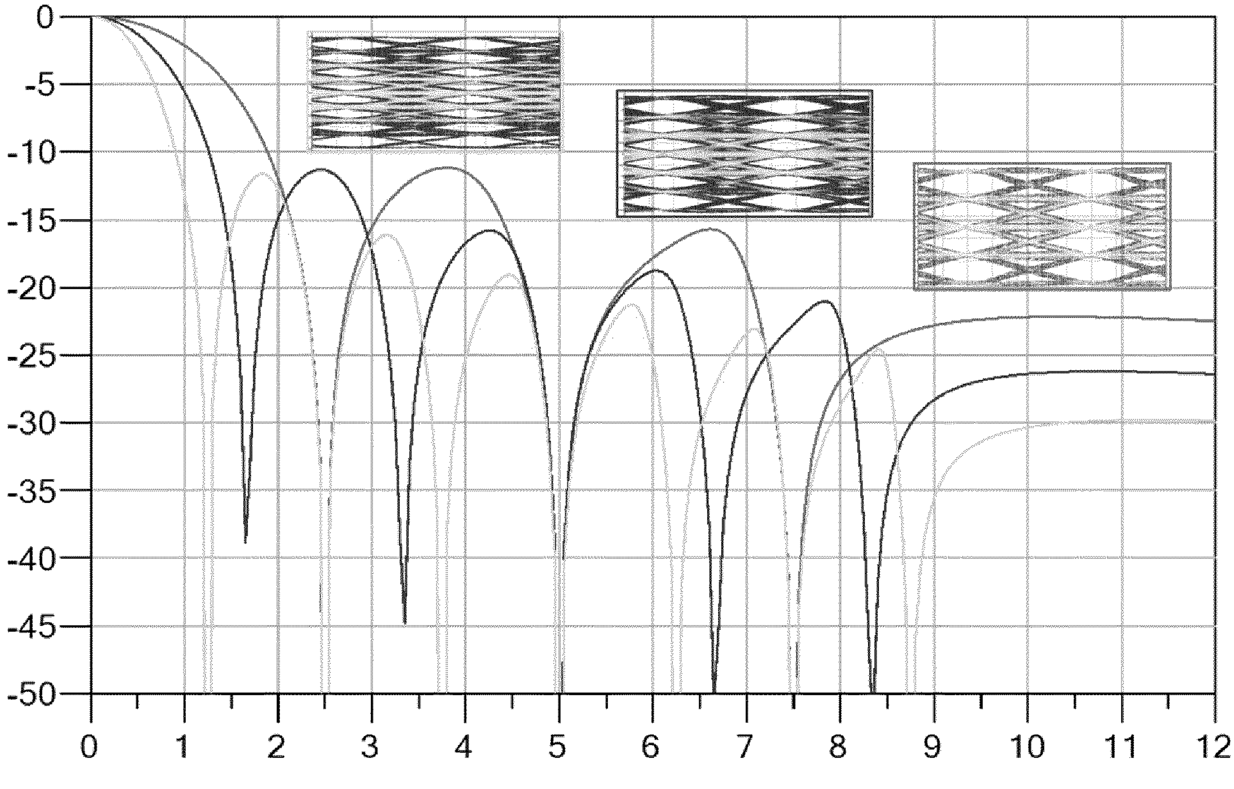


Fig. 15

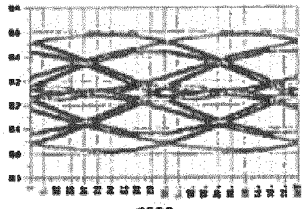
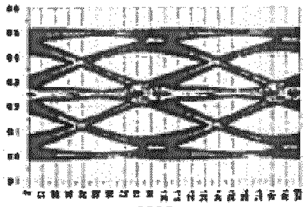
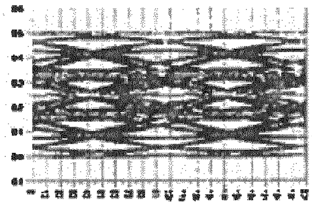
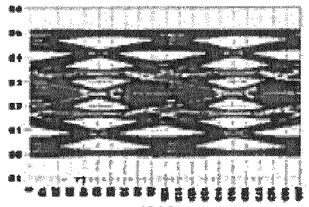
Modulation	Scheme	Eye diagram (V)	Bessel LPF specs	Bessel BSF specs
5-level polybinary	Standard		f_{3dB}=1.9 GHz 4[rd] order	-
	A		f_{3dB}=1.9 GHz 3[rd] order	f_{center}=5 GHz Δ_{3dB}=0.5 GHz 1[st] order
7-level polybinary	Standard		f_{3dB}=1.3 GHz 8[rd] order	-
	A		f_{3dB}=1.3 GHz 3[rd] order	f_{center}=3.33 GHz Δ_{3dB}=0.5 GHz 1[st] order

Fig. 16

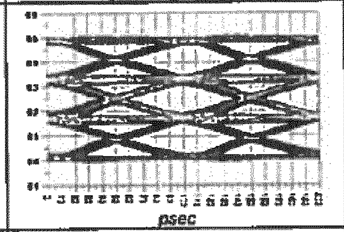
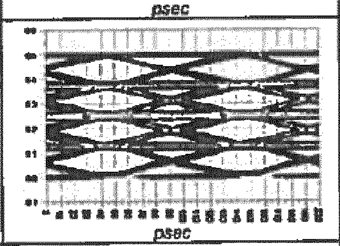
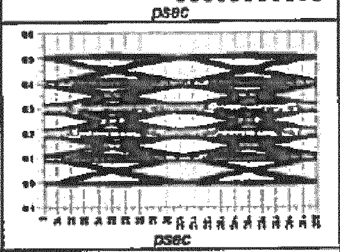
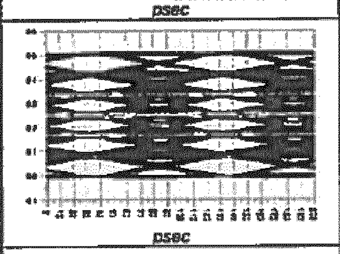
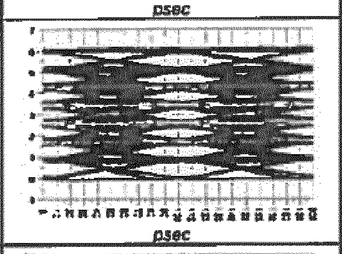
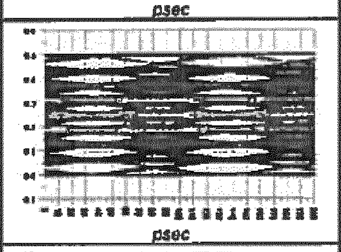
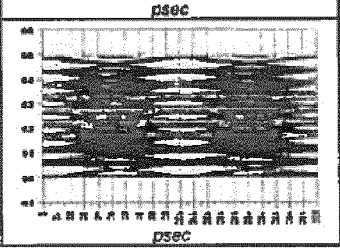
Modulation	Eye diagram (V)	Bessel LPF specs	*m*-2 Bessel BSFs specs
4-level polybinary		f_{3dB}=1 GHz 1st order	f_{center}=k·3.33 GHz Δ_{3dB}=0.8 GHz 1st order k=1,2
5-level polybinary		f_{3dB}=1 GHz 1st order	f_{center}=k·2.5 GHz Δ_{3dB}=1 GHz 1st order k=1,2,3
6-level polybinary		f_{3dB}=0.9 GHz 1st order	f_{center}=k·2 GHz Δ_{3dB}=0.9 GHz 1st order k=1,2,3,4
7-level polybinary		f_{3dB}=0.7 GHz 1st order	f_{center}=k·1.67 GHz Δ_{3dB}=0.6 GHz 1st order k=1,2,3,4,5
8-level polybinary		f_{3dB}=0.6 GHz 1st order	f_{center}=1.43 GHz Δ_{3dB}=0.6 GHz 1st order k=1,2,3,4,5,6
9-level polybinary		f_{3dB}=0.5 GHz 1st order	f_{center}=k·1.25 GHz Δ_{3dB}=0.5 GHz 1st order k=1,2,3,4,5,6,7
10-level polybinary		f_{3dB}=0.4 GHz 1st order	f_{center}=k·1.11 GHz Δ_{3dB}=0.4 GHz 1st order k=1,2,3,4,5,6,7,8

Fig. 17

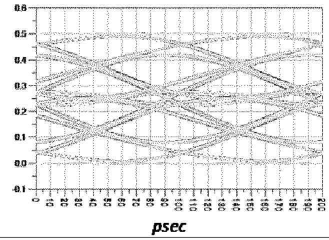
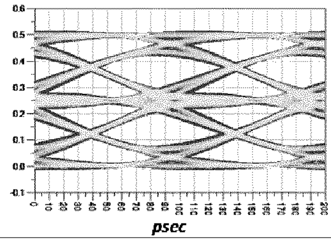
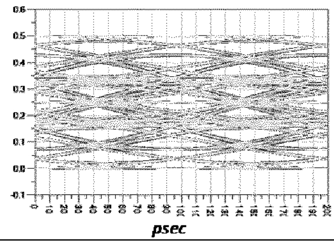
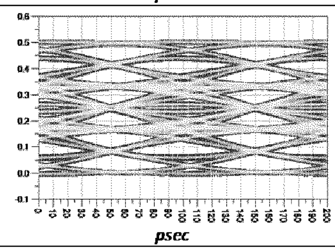
Modulation	Scheme	Eye diagram (V)	Bessel LPF specs	Bessel BSF specs
5-level polybinary	Standard		f_{3dB}/f_p=0.19 4rd order	-
	A		f_{3dB}/f_p=0.19 3rd order	f_c/f_p=0.5 Δ_{3dB}/f_p=0.05 1st order
7-level polybinary	Standard		f_{3dB}/f_p=0.13 8rd order	-
	A		f_{3dB}/f_p=0.13 3rd order	f_c/f_p=0.33 Δ_{3dB}/f_p=0.5 1st order

Fig. 18

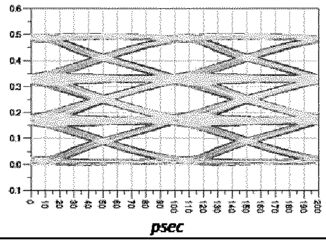
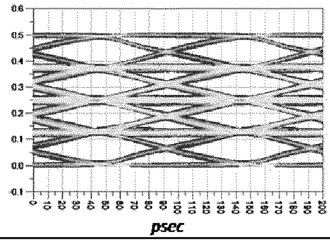
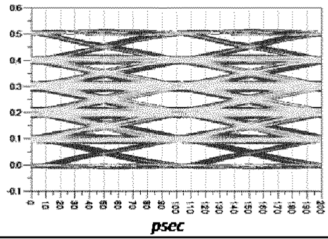
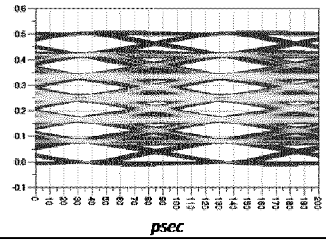
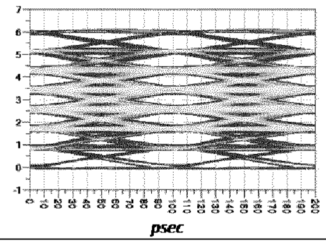
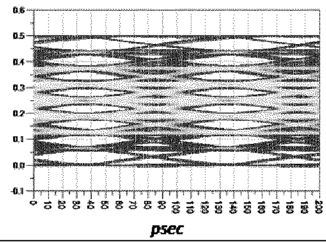
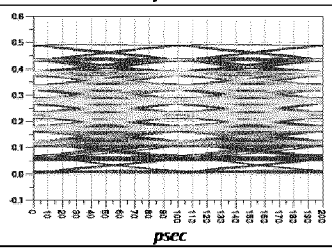
Modulation	Eye diagram (V)	Bessel LPF specs	*m-2* Bessel BSFs specs
4-level polybinary		f_{3dB}/f_p=0.1 1st order	f_{ck}/f_p =k·0.33 Δ_{3dB}/f_p=0.8 GHz 1st order k=1,2
5-level polybinary		f_{3dB}/f_p=0.1 1st order	f_{ck}/f_p=k·0.25 Δ_{3dB}/f_p=0.1 1st order k=1,2,3
6-level polybinary		f_{3dB}/f_p=0.09 1st order	f_{ck}/f_p=k·0.2 Δ_{3dB}/f_p=0.09 1st order k=1,2,3,4
7-level polybinary		f_{3dB}/f_p=0.07 1st order	f_{ck}/f_p=k·0.167 Δ_{3dB}/f_p=0.06 1st order k=1,2,3,4,5
8-level polybinary		f_{3dB}/f_p=0.06 1st order	f_{ck}/f_p= k·0.43 Δ_{3dB}/f_p=0.06 1st order k=1,2,3,4,5,6
9-level polybinary		f_{3dB}/f_p=0.05 1st order	f_{ck}/f_p=k·0.125 Δ_{3dB}/f_p=0.05 1st order k=1,2,3,4,5,6,7
10-level polybinary		f_{3dB}/f_p=0.04 1st order	f_{ck}/f_p=k·0.111 Δ_{3dB}/f_p=0.04 1st order k=1,2,3,4,5,6,7,8

Fig. 19

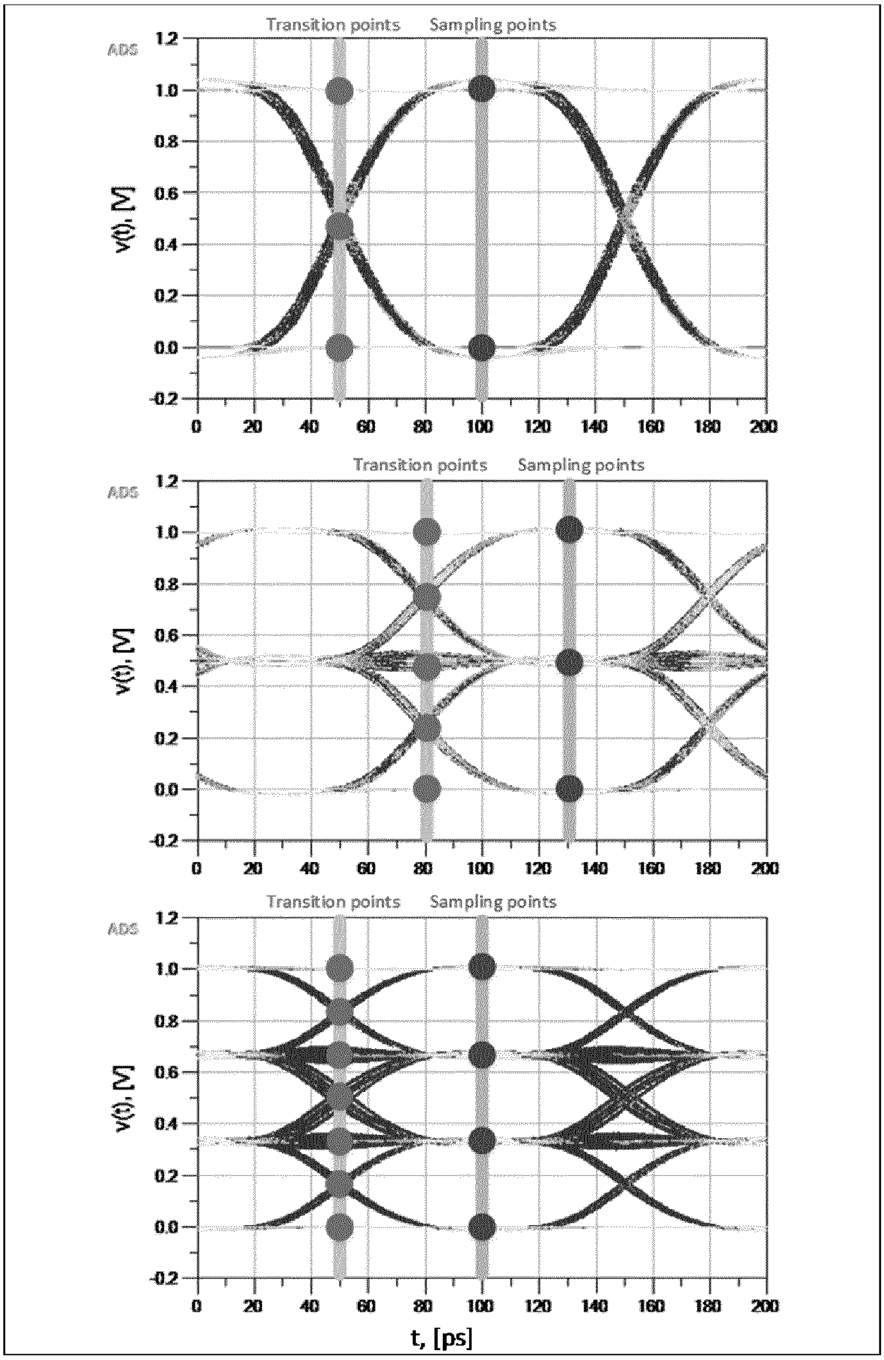

Transition points
Sampling points
ADS
v(t), [V]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0
20
40
60
80
100
120
140
160
180
200
t, [ps]

Fig. 20

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/067745

A. CLASSIFICATION OF SUBJECT MATTER
INV. H04L25/49
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H04L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	VEGAS OLMOS JJ ET AL: "Challenges in Polybinary Modulation for Bandwidth Limited Optical Links", JOURNAL OF LASERS, OPTICS & PHOTONICS, vol. 3, no. 1, 15 January 2016 (2016-01-15), XP055341367, DOI: 10.4172/2469-410X.1000127 the whole document -----	1-9, 14-23, 28-35 10-13, 24-27
A	US 2015/256361 A1 (SUN CHEN-KUO [US] ET AL) 10 September 2015 (2015-09-10) abstract paragraph [0002] - paragraph [0004] paragraph [0007] - paragraph [0010] paragraph [0020] - paragraph [0023] paragraph [0027] figure 1 -----	1-35

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
8 September 2017	19/09/2017

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Schiffer, Andrea

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2006/043268 A1 (TERASEA LTD [IL]; AVIGDOR MOSHE [IL]; DADON RONI [IL]) 27 April 2006 (2006-04-27) abstract first paragraph; page 5 paragraph starting with "Referring now to Figs. 9 and 10..."; page 8 -----	1-35

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2017/067745

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2015256361 A1	10-09-2015	NONE	
WO 2006043268 A1	27-04-2006	NONE	