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TRANSMITTER AND RECEIVER FOR OPTICAL COMMUNICATION SYSTEMS

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TRANSMITTER AND RECEIVER FOR OPTICAL COMMUNICATION SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority of US provisional patent application no. 60/938,540 filed on May 17, 2007, the specification of which is hereby incorporated by reference.

TECHNICAL FIELD

[0002] The present relates generally to devices and methods used in optical communication systems. More specifically, it relates to the encoding and decoding of optical signals in multiplexed access optical communication systems.

BACKGROUND

[0003] Today's Wavelength Division Multiplexing (WDM) and Optical Code Division Multiplexing Access (OCDMA) communication systems are under intense scrutiny for future broadband access. In classical transmitters, the broadband source is sliced using an optical filtering device, such as a fiber Bragg grating in reflection mode, a thin film or a diffraction grating. Each user is assigned a subset of n wavelengths, where n = 1 for Spectrum Sliced WDM (SS-WDM). The user's data sequence modulates the sliced broadband source and the modulated signal is propagated through the network.

[0004] In conventional SS-WDM optical communications (see for example McCoy et al., "Noise Suppression of Incoherent Light Using a Gain-Saturated SOA: Implications for Spectrum-Sliced WDM Systems", *IEEE J. Lightwave Tech.*, Vol. 23, No. 8, pp. 2399-2409, Aug. 2005.), the receiver is a slicing device matched to the transmitter, i.e. it has an optical filter which selects the appropriate user channel followed by direct detection of the filtered signal.

[0005] A wide variety of OCDMA systems and receivers exist in prior art. These systems can be split into three main categories:

1) Wavelength-time (λ – t) systems (see, for example, U.S. Patent No. 6,381,053 to Fathallah et al.);

2) Spectral Amplitude Coded (SAC) OCDMA systems (see, for example, Kavehrad, *et al.,* ''Optical code-division-multiplexed systems based on spectral encoding of incoherent sources'', *Journal of Lightwave Technology*, Vol. 13, pp 534-545, March 1995); and

3) Time only systems, where short duration pulses are distributed throughout a bit interval and where a receiver recombines these pulses into an autocorrelation peak **Auriez-vous une reference à suggérer pour cette approche?**.

[0006] These systems all suffer major limitations because of excess intensity noise.

[0007] Coherent OCDMA systems such as the one disclosed by Brackett et al. in U.S. patent no. 4,866,699, suffer from high receiver complexity and high system cost because of the use of mode-locked lasers.

[0008] On the other hand, OCDMA systems using incoherent sources are attractive because they are potentially more cost effective and more spectrally efficient than WDM systems (see J. A. Salehi, ‘‘Code division multiple-access techniques in optical fiber networks. I. Fundamental principles’’, *IEEE Transactions on Communications*, Vol 37, pp 824-833, Aug. 1989). Two versions of such OCDMA systems are the most promising.

[0009] Firstly, consider ‘‘Optical code-division-multiplexed systems based on spectral encoding of incoherent sources’’, *Journal of Lightwave Technology*, Vol. 13, pp 534-545, March 1995, where Kavehrad, et al., introduces SAC OCDMA. Coding only occurs in the spectral domain. Although it uses balanced detection for Multiple Access Interference (MAI) suppression, this scheme is limited by excess intensity noise.

[0010] Secondly, consider U.S. patent No. 6,381,053, where Fathallah et al. use time and wavelength to encode information, i.e., wavelength-time or Fast Frequency Hopped (FFH) coding. Wavelength-time systems typically use a spectro-temporal decoder that is a mirror replica of the encoder device. One common way to encode the optical signal is to slice an optical pulse from the broadband source into several wavelength bands, and to introduce to each band distinct time delay. At the receiver, the decoding operation is realized with an optical filter with the same wavelengths but with a function that is complementary to the encoding filter. This system also suffers from excess intensity noise limitations.

[0011] There is therefore a need for transmitters and/or receivers capable of mitigating noise and interference in a spectrally efficient way, for both WDM and OCDMA systems.

SUMMARY

[0012] There is provided transceivers for both Spectrum Sliced Wavelength Division Multiplexing (SS-WDM) and incoherent Optical Code Division Multiplexing Access (OCDMA) systems capable of enhancing the quality of the received signal before photo-detection. A balanced receiver is used to limit the intra-channel crosstalk as well as the additive amplified spontaneous emission (ASE) noise in the amplified SS-WDM case. The combination of an optical amplifier transmitter and a balanced receiver reduces excess intensity noise (also called beat noise and phase induced intensity noise) in the case of both WDM and OCDMA systems with optical incoherent broadband sources and also in the case of OCDMA systems using coherent sources.

[0013] According to one aspect of the invention, there is provided a receiver using balanced detection which is capable of limiting at least one of intra-channel crosstalk, ASE noise and multiple access interference in a SS-WDM system using incoherent sources. The use of balanced detection increases spectral efficiency and robustness to variation in signal power throughout the communications link.

[0014] According to another aspect of the invention, there is provided 1) a new receiver architecture using balanced detection which is capable of limiting at least one of intra-channel crosstalk, ASE noise and multiple access interference, and 2) an optical amplifier at the transmitter after the encoding operation. The optical amplifier can, for example, be a semiconductor optical amplifier (SOA) or hybrid AlGaInAs-silicon evanescent amplifier. Hybrid Evanescent Optical Amplifiers (HEOA) bring the possibility of integration of the entire transmitter in single small low cost chip. The provided new configuration uses the combination of the optical amplifier in the transmitter with the provided balanced receiver which allows for almost total noise suppression and hence an increase in performance.

[0015] According to yet another aspect of the invention, an optical amplifier is used in a transmitter, before performing external data modulation. When used in combination with the provided balanced receiver, these transmitters afford substantial excess intensity noise suppression without sacrificing spectral efficiency. With the use of balanced detection in combination with an optical amplifier at the transmitter before external modulation, noise suppression is achieved and multiple rate transmissions are supported with greater spectral efficiency and/or increased transmission rate. An increase in the achievable bit rate may also be provided.

[0016] – We will insert here statements of the invention --

[0017] It is noted that throughout this document, noise suppression is meant to mean a reduction of the noise to an acceptable level for optical communication practical purposes, i.e. to obtain an acceptable transmission error rate. It is not required that the noise be completely eliminated.

[0018] Also, throughout this document, “optical multiplexed communication” is an expression meant to include both WDM and OCDMA communication.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Fig. 1 is a block diagram showing a SS-WDM receiver according to an example embodiment;

[0020] Fig. 2 is a block diagram showing an incoherent SAC-OCDMA receiver according to an example embodiment, where Fig. 2A shows the behavior of the receiver when receiving a user encoded signal and Fig. 2B, when receiving B an interference encoded signal;

[0021] Fig. 3 is a block diagram showing a Wavelength Division Multiplexing (WDM) transmitter which can be used in conjunction with the receiver of Fig. 1 and wherein the noise suppression device is a semiconductor optical amplifier;

[0022] Fig. 4 is a block diagram showing a silicon SS-WDM transmitter which can be used in conjunction with the receiver of Fig. 1 and wherein the noise suppression device is a hybrid evanescent optical amplifier;

[0023] Fig. 5 is a block diagram showing an incoherent SAC-OCDMA transmitter which can be used in conjunction with the receiver of Fig. 2;

[0024] Fig. 6 is a block diagram showing a transmitter with a saturated optical amplifier according to another embodiment wherein the optical amplifier is used for both noise suppression and modulation;

[0025] Fig. 7 is a block diagram showing a transmitter incorporating a saturated optical amplifier according to yet another embodiment wherein the optical amplifier is placed after the electro-optical modulation;

[0026] Fig. 8 is a block diagram showing SS-WDM transmitter which can be used in conjunction with the receiver of Fig. 1 and based on a self re-injection of a reflective semiconductor optical amplifier;

[0027] Fig. 9 is a graph showing… to be completed**

[0028] Fig. 10 is a block diagram showing another SS-WDM transmitter which can be used in conjunction with the receiver of Fig. 1 and based on a self re-injection of a semiconductor optical amplifier;

[0029] Fig. 11 is a block diagram showing an example architecture of a SS-WDM Passive Optical Network which use the transmitter of Fig. 8 at the optical network unit side and the receiver of Fig. 1 at the optical line terminal side;

[0030] Fig. 12 is a block diagram of an experimental setup of a WDM transmission system using the transmitter of Fig. 4 and the receiver of Fig. 1;

[0031] Fig. 13 is a graph showing the Q-factor experimental results as a function of the bit rate obtained with the experimental setup of Fig. 12, for five different transmission system configurations;

[0032] Fig. 14 is a graph showing bit error rate (BER) experimental results at 5 Gbps for the transmission system of the experimental setup of Fig. 12, under various loads; and

[0033] Fig. 15 is a graph comparing the bit error rate (BER) experimental results of the balanced and the conventional receiver of the experimental setup of Fig. 12, at 10 Gbps.

[0034] It will be noted that throughout the appended drawings, like features are identified by like reference numerals.

DETAILED DESCRIPTION

[0035] The present concerns Optical Amplifier (OA) based transmitters and balanced detection receivers particularly adapted to incoherent Wavelength Division Multiplexing (WDM) and both incoherent and coherent Optical Code Division Multiplexing Access (OCDMA) telecommunication systems. According to a first aspect, there is provided a balanced detection receiver able to suppress interference, either crosstalk interference or multiple access interference, as well as other additive noises in the link. More particularly, in several example embodiments which will be detailed hereinafter, the receiver is used in WDM, Spectral Amplitude Coded OCDMA (SAC-OCDMA) and Fast Frequency Hopped (FFH) OCDMA systems. **Would it be possible to replace the SAC filter by a wavelength-time filter for use in wavelength-time OCDMA systems?**

[0036] Fig. 1 shows an example balanced WDM receiver 100 for use in the Spectrum Sliced WDM (SS-WDM) systems. The receiver 100 is for decoding a SS-WDM signal corresponding to a given end-user. The receiver 100 comprises an input optical fiber 10 adapted to be connected to an optical communication network to receive from the network the signal to be decoded. The received signal comprises encoded data addressed to a plurality of users, i.e. the data addressed to the plurality of users is multiplexed on the received signal. The receiver 100 decodes the received signal to retrieve the signal addressed to the given end-user which it is set to decode. At the transmitter, the signal addressed to the given end-user is encoded with a specific spectral access function [λ_{user}] associated with the end-user. In this case of SS-WDM decoding, the spectral access function is a spectrum-sliced function, i.e. each user is allocated a single wavelength channel.

[0037] The input optical fiber 10 is connected to an input of a 1x2 optical splitter 20, a 50/50 optical fiber coupler in this case. The two outputs of the optical splitter 20 are respectively connected to a first and a second optical fiber path 30 and 40. The first optical fiber path 30 has a filter 32 which spectral response is the spectral complement function $\overline{\lambda_{user}}$ of the spectral access function of the end-user, i.e. the filter 32 filters out the user's channel wavelength but let through all other channel wavelengths. The second optical path 40 has no filtering, herein denoted by the Optical Delay Line 42 (ODL) just to emphasize the fact that the optical lengths of both paths 30, 40 are equal so that all additive noises occurring during the link, as well as crosstalk channels, cancel out during balanced detection. However, the ODL typically consists of a piece of optical fiber which length is adjusted so that the lengths of both paths 30, 40 are equal. A Variable optical Attenuator 44 (VA) is also typically placed on the second path 40. The ends of the first and second paths 30, 40 are connected to a balanced photodetector 50, respectively on the positive negative input and the positive input of the balanced photodetector 50. The output 60 of the balanced photodetector 50 is an electrical signal representative on of the decoded data addressed to the end-user.

[0038] Accordingly, the signal received from the optical communication network on the input optical fiber 10 is first split into two optical paths 30 and 40 using the 1x2 optical splitter 20. In the first path 30, the user signal (at λ_{user}) is blocked, i.e. signal on the wavelength channel associated with the user channel is dropped and all the other channels are let through. This is depicted on Fig. 1 as the spectral complement function $\overline{\lambda_{user}}$.

[0039] The transmitter and receiver filters may be matched during fabrication. For example, the encoding filter of the transmitter is a Fiber Bragg Grating (FBG) used in reflection to slice only the channel wavelength associated with the user. At the receiver 100, the filter 32 is then made of an identical FBG that is used in transmission to provide a notch filter that corresponds to the spectral complement function $\overline{\lambda_{user}}$.

[0040] For all wavelength channels except the user channel, both paths 30, 40 let the signal through. The balanced photodetector 50 detects a power difference between the outputs of the second and the first path 40, 30. Accordingly, the optical power received from the first and the second paths 30, 40 respectively at the negative and positive inputs of the balanced photodetector 50 cancels out for all channels but the user channel.

[0041] In the user channel, the second path 40 lets the signal through, while signal in the user channel is blocked by the filter 32 in the first path 30. The balanced photodetector 50 detects a power difference between the outputs of the second and the first path 40, 30 and therefore detects the optical power within the user channel. The output 60 of the balanced photodetector 50 is therefore representative of the data addressed to the user.

[0042] For good suppression results, the two optical paths 30, 40 should be adjusted to have substantially equal optical losses and optical path lengths. The optical loss of the second path 40 is adjusted using the variable optical attenuator 44. As a result, when the data addressed to the user corresponds to a logical zero, the optical powers at the first and the second optical paths 30, 40 are equal. The output of the balanced photodetector 50 then gives a logical zero. When the data addressed to the user corresponds to a logical one, the optical power at the output of the second path 40 is higher than that of the first path 30, and the output 60 of the balanced photodetector 50 gives a logical one.

[0043] For good suppression results, the optical path lengths of the two paths 30, 40 should be sufficiently equal to allow noise samples to hit the balanced photodetector 50 synchronously, even though they have traveled in different optical paths. In one embodiment, the optical delay line 42 consists of a simple piece of optical fiber which length is adjusted such that the resulting optical path lengths of the two paths 30, 40 are substantially equal.

[0044] Note that, except for the added optical splitter 20 and the balanced photodetector 50, the complexity of the receiver 100 remains fairly comparable to that of the simplest SS-WDM optical receivers.

[0045] Fig. 2 shows an example receiver 200 for use in a SAC-OCDMA system using incoherent light sources. Fig. 2A illustrates the detection of user encoded signal using the receiver 200, while Fig. 2B illustrates the suppression of interference signal, i.e. addressed to other users. The receiver 200 of Fig. 2 is in most points similar to the receiver 100 of Fig. 1 and similar components will not be herein repetitively described. The difference between the receivers 100 and 200 lies in the filter 232 which in the case of Fig. 2 is adapted to decode SAC-OCDMA encoded signals. The spectral response of the filter 232 therefore corresponds to the spectral complement function $\overline{\lambda_{user}}$ of the SAC-OCDMA encoding filter of the transmitter used to encode the user encoded signal.

[0046] As in the receiver 100 of Fig. 1, the encoded signal coming from the network is split into a first and a second optical path 30, 40 at the receiver 200. The first optical path 30 has a filter 232 which spectral response is the spectral complement function of the OCDMA spectral access code function corresponding to the user. In the illustrated case (see Fig. 2A), the OCDMA code is a seven-wavelength code and the user's spectral access code is $[\lambda_{user}] = [\lambda_1, \lambda_2, \lambda_4]$. The spectral complement function is therefore $[\overline{\lambda_{user}}] = [\lambda_3, \lambda_5, \lambda_6, \lambda_7]$, i.e. λ_3, λ_5, λ_6 and λ_7 are let through while λ_1, λ_2, λ_4 are blocked. In the second path 40, the variable optical attenuator

44 is used to balance the multiple access interference as in prior art SAC balanced detection. The attenuation value depends on the cross-correlation of the OCDMA codes.

[0047] In this case, the encoder filter and the decoder filter 232 are made of FBG filters which are readily fiber compatible. The encoder filter uses a first FBG in reflection while the decoder filter 232 uses a second FBG identical to the first one but used in transmission. Other types of filters such as thin films and diffraction gratings may be used as well.

[0048] Fig. 2A illustrates the detection of user encoded signal using the receiver 200. In this case, the user OCDMA spectra access function, i.e. the OCDMA code, is $[\lambda_{user]} = [\lambda_1, \lambda_2, \lambda_4]$. When a signal according to this code is received on the input optical fiber 10 of the receiver 200, the filter 232 with the spectral complement function $\left[\overline{\lambda_{user}}\right]=[\lambda_3,\lambda_5,\lambda_6,\lambda_7]$ blocks the user encoded signal while the encoded signal is let through the second path 40. The balanced photodetector 50 therefore detects a differential optical power that corresponds to the user encoded signal and the detected signal at the output 60 of the balanced photodetector 50 is representative of the data addressed to the user.

[0049] Fig. 2B illustrates the detection of an interference encoded signal using the receiver 200. In this illustrated case, the code of the interference encoded signal is $[\lambda_{interf]} = [\lambda_2, \lambda_3, \lambda_5]$. When a signal according to this code is received on the input optical fiber 10 of the receiver 200, the filter 232 with the spectral complement function $\left[\overline{\lambda_{user}}\right]=[\lambda_3,\lambda_5,\lambda_6,\lambda_7]$ partly lets through the interference encoded signal while the interference encoded signal is let completely through the second path 40. The variable optical attenuator 44 is used to balance the multiple access interference as in prior art SAC balanced detection. The attenuation value is adjusted given the cross-correlation of the OCDMA codes. **Is the attenuation adjusted dynamically or set once as a function of parameters of the system? Would you be able to complete the information here regarding the attenuation adjustment? Thanks.** In this case, the optical attenuation is set to 2/3 or 1.76 dB such that the optical power received from the first path 30 encounters the optical power received from the second path 40 at the balanced photodetector 50. The interference coded signal is therefore suppressed.

[0050] The receivers of Figs. 1 and 2 allow cost effective access network solutions when compared with the state of the art schemes.

[0051] A configuration of OA-based transmitters is now discussed. When used in combination with the receivers described above, these transmitters afford excess intensity noise suppression without sacrificing spectral efficiency.

[0052] Now referring to Fig. 3, an example optical WDM transmitter 300, which can be used in conjunction with the receiver 100 described above, is described. Spectrum slicing uses a single broadband light source 310 which is split in power onto multiple optical paths 314 using an optical splitter 312. There are as many optical paths 314 as there are WDM channels. The various WDM channels are provided by spectral slice filters 316, which act as encoders. One spectral slice filter 316 is provided on each optical path 314, following the optical splitter 312 and each spectral slice filter 312 corresponds to one of the WDM channels. Following each spectral slice filters 316, a Semiconductor Optical Amplifier (SOA) 318 is used as a noise suppression device. The SOA 318 is used to suppress the intensity noise on each individual channel prior to modulation. The SOA 318 is operated in saturation and is placed just after slicing and prior to modulation. This technique suppresses noise fluctuations over several gigahertzes independently of the SOA dynamic response. The resultant signal passes through a Polarization Controller 320 before being modulated by an electro-optical modulator 322. The modulated signals are then combined using an optical multiplexer 324.

[0053] A key drawback of prior art spectrum sliced systems is the high degree of excess intensity noise, which can dramatically impair system performance. It should be noted that the superior signal quality offered by the suppression technique of the transmitter 300 of Fig. 3 would be noticeably degraded if it was used with a conventional receiver (see, for example, McCoy et al., “Noise Suppression of Incoherent Light Using a Gain-Saturated SOA: Implications for Spectrum-Sliced WDM Systems”, *IEEE J. Lightwave Tech.*, Vol. 23, No. 8, pp. 2399-2409, Aug. 2005.), since the superior signal quality is degraded by an optical filtering at the receiver. Filtering is unavoidable in conventional receiver. However, when this noise suppression technique is combined with the decoding scheme of the receiver 100 of Fig. 1, the signal quality is not degraded as much substantially maintained.

[0054] Accordingly, in one configuration, the SOA-based transmitter 300 is combined with the balanced receiver 100 of Fig. 1. To illustrate this embodiment, consider an incoherent SS-WDM system where the data sent by the transmitter 300 corresponds to a logical one. Suppose that only one user is transmitting, and that this signal is incident on the receiver 100 of Fig. 1. The excess intensity noise is significantly suppressed by the SOA 318 at the transmitter 300. In the second optical path 40 of the receiver 100, a clean signal with a logical one power is received on the positive input of the balanced photodetector 50. At the same time, in the first optical path 30, the signal is mostly blocked by the filter 32. This results, at the output 60 of the balanced photodetector 50, in a zero level with very low noise. In fact, the filter 32 can be seen as a wide optical filter that accomplishes most of the noise cleaning. The differential detection results in a detected logical one level without any significant intensity noise, in contrast to conventional receivers. When the data sent by the transmitter 300 corresponds to a logical zero, the noise is not major issue since the power level of the signal is low. Consider now the superposition of the user channel with many other SS-WDM channels. The filtering strategy in the receiver 100 of Fig. 1 leads to all signal in the other SS-WDM channels being incident on both sides of the balanced photodetector 50 simultaneously, so that this signal is zeroed out at the output 60 of the balanced photodetector 50, leaving only the user encoded signal with suppressed excess intensity noise.

[0055] It is noted that the use of balanced detection in combination with an optical amplifier at the transmitter before external modulation provides efficient noise suppression and good spectral efficiency. It also helps to increase the achievable transmission rate compared to conventional configurations. Furthermore, it may allow for supporting multiple rate transmissions with greater spectral efficiency and/or increased transmission rate.

[0056] Fig. 4 shows another embodiment of a WDM transmitter 400 which is adapted for full integration on a single silicon photonic chip. The transmitter 400 uses a Hybrid Evanescent Optical Amplifiers (HEOA) as the noise suppression device. The output of a broadband light source 410, typically an incoherent light source, is connected to a wavelength demultiplexing arrayed waveguide grating 412, in this case a silicon-on-insulator arrayed waveguide grating (see P.D. Trinh, S. Yegnanarayanan, F. Coppinger, and B. Jalali, “Silicon-on-insulator (SOI) phased-array wavelength multi-demultiplexer with extremely low-polarization sensitivity,” *IEEE Photon. Technol. Lett*., vol. 9, no. 7, pp. 940-942, July 1997 for an example of SOI-AWG). The arrayed waveguide grating 412 splits the broadband light in wavelength onto a plurality of optical paths 414, such that each optical path 414 carries its individual WDM channel. A hybrid amplifier 418, such as a hybrid AlGaInAs-silicon amplifier, is placed on each optical path 414, at each of the WDM outputs of the arrayed waveguide grating 412. The hybrid amplifier is used to suppress the intensity noise on each individual WDM channel prior to modulation. The hybrid amplifiers 418 are operated in saturation and are placed just after slicing and prior to modulation. This technique typically suppresses noise fluctuations over several gigahertzes. The excess intensity noise of the main mode propagating into the silica waveguide is coupled to the hybrid amplifier 422 through evanescent wave coupling. The saturated amplifier 422 suppresses the noise similarly to the SOA 318 in the transmitter 300 of Fig. 3 and the noise of the mode propagating in the silicon waveguide region is substantially suppressed. On each optical paths 414, the output of each hybrid amplifier 418 is then connected to the input of a silicon-based electro-optical modulator 422 modulated by the data to be transmitted using the corresponding WDM channel (see L. Liao, D. Samara-Rubio, M. Morse, A. Liu, D.Hodge, D. Rubin, U. Keil, and T. Frank, “High speed silicon Mach-Zehnder modulator, ” *Opt. Express*, vol. 13, no. 8, pp.3129-3135, Apr. 2005 for an example of a modulator). The end of the optical paths 414 are then connected to a multiplexer 424, e.g. a passive silicon coupler, which combines all the WDM channels back in a single optical fiber 426 for transmission over the network. Hence, using a HEOA-based transmitter 400, a full silica-based transmitter device is provided. Integration of the whole optical line terminal (OLT) or integration of the whole central office (CO) on a single silicon photonic chip becomes possible.

[0057] Fig. 5 shows an example of a transmitter 500 to be used in a SAC-OCDMA system along with the receiver 200 of Fig. 2. The transmitter 500 is in most points similar to the transmitter 300 of Fig. 3 and similar components will not be herein repetitively described. In order to provide a SAC-OCDMA transmitter 500, the spectral slice filters 316 of the transmitter 300 of Fig. 3 are replaced by SAC-OCDMA encoding filters 516. Each encoding filter 516 has a spectral response corresponding to the spectral access function of its associated user. As in Fig. 3, both the encoding filter 516 and the optical amplifier 318, which can be a SOA, a HEOA or another optical amplifier in this case, are placed before the modulator 322, which provides substantial noise cleaning. In the transmitter 500, the encoding filter 516 consists of a multi-wavelength reflective grating 532, a series of cascaded FBGs in this case, connected to port 2 of a three-port optical circulator 534 in order to use the multi-wavelength reflective grating 532 in reflection. The receiver 200 used in combination with the transmitter SOA uses a filter 32 that has a spectral response which corresponds to the spectral complement function of the encoding filter 516. In the present case, the transmitter 500 and the matched receiver 200 use identical reflective gratings, but in inverse mode, i.e. the reflective grating is used in transmission in the receiver 200 while it is used in reflection in the transmitter 500 (or vice-versa). It is noted that the multi-wavelength reflective grating 532 may also be made of a superimposed grating or a silicon-on-insulator arrayed waveguide grating.

[0058] Fig. 6 shows another embodiment of a transmitter 600 to be used in a SAC-OCDMA system along with the receiver 200 of Fig. 2. The transmitter 600 is in most points similar to the transmitter 500 of Fig. 5 and similar components will not be herein repetitively described. The difference between the transmitter 600 of Fig. 6 and the transmitter 500 of Fig. 5 is that, in the transmitter 600, the modulator is integrated in the optical amplifier 618 which is used for both noise suppression and modulation. Accordingly, no separate modulator is used and the polarization controller 320 is placed before the modulator/amplifier 618. This configuration however limits the maximal achievable bit rate to that of the modulation bandwidth of the modulator/amplifier 618 (around 10 GHz for SOAs). Nevertheless, the use of an integrated modulator/amplifier 618 in combination with an OCDMA or WDM receiver as described above, provides good robustness against intensity noise, interference and other additive noise sources.

[0059] Fig. 7 shows yet another embodiment of a transmitter 700 to be used in a SAC-OCDMA system along with the receiver 200 of Fig. 2. The transmitter 700 is also in most points similar to the transmitter 500 of Fig. 5 and similar components are not herein repetitively described. In this case, the difference between the transmitter 700 of Fig. 7 and the transmitter 500 of Fig. 5 is that, in the transmitter 700, a single optical amplifier 718 is used after the optical multiplexer 324, the optical amplifiers 318 being removed from the individual optical paths 314. This configuration allows the sharing the optical amplifier 718 among several users instead of an individual optical amplifier 718 for each user. In this case, the common optical amplifier 318 is used as both a booster and a noise cleaner for all the OCDMA channels. Although this configuration is more cost effective, it should be noted that the combination of the transmitter 700 with the receiver 200 is less efficient for excess intensity noise suppression. The amplified spontaneous emission generated by the optical amplifier 318 is modulated through cross-gain modulation and detected at the receiver 200, reducing the noise reduction performance. Moreover, the transient response of the optical amplifier gain can produce patterning effects that give rise to eye pattern distortion.

[0060] Fig. 8 shows a SS-WDM transmitter 800 based on a self re-injected Reflective Semiconductor Optical Amplifier (ROSA), and which may be used with the receiver 100 of Fig. 1 in a SS-WDM optical communication system. The transmitter 800 uses a RSOA 810 as the light source that is directly modulated. The input current of the RSOA 810 is modulated with the data to be transmitted at a low extinction ratio and at high current levels. This modulation is transferred to modulated Amplified Spontaneous Emission (ASE). The output of the RSOA 810 is connected to port ‘2’ of a three-port optical circulator 820. The output of port ‘3’ of the circulator 820 is connected to an optical splitter 830, a 50/50 fiber coupler in this example, which splits the modulated ASE between the transmitter output 832 and a re-injection loop 834. In the re-injection loop the modulated ASE is filtered using a band pass slice filter 840 of which the output is connected to port ‘1’ of the optical circulator 820 for re-injection to the RSOA 810 through port ‘2’ of the optical circulator 820. The ASE re-injected to the RSOA 810 has sufficient power for the RSOA to operate in saturation.

[0061] Re-injecting the RSOA 810 with a specific wavelength favors its output/gain at that wavelength, therefore the ASE is lowered and the desired channel is amplified, effectively siphoning off power from the ASE to the desired channel. While such a configuration gives greater power efficiency and allows data to directly modulate the source, it also provides noise cleaning provided the RSOA 810 is appropriately saturated. The noise cleaning can be retained in a SS-WDM system when the receiver 100 of Fig. 1 is used. Since the light source is being directly modulated, such a transmitter is well adapter for use on the client side of the network.

[0062] **Would it be possible to use a self reinjected RSOA of SAC-OCDMA encoding?**

[0063] Fig. 9 shows an experimental result of the **Please indicate what is shown in Fig. 9, including the difference between the solid line and the dashed line.**. In this case, the RSOA 810 is a CIP SOA-R-OEC-1550 manufactured by CIP Technologies^{TM}, Ipswich, United Kingdom. It can be seen that a 30 dB of noise suppression is achieved when the current the RSOA 810 is directly modulated at 1.25 Gb/s. An experimental validation of the noise cleaning potential of the transmitter 800 is provided by comparing its performance with a prior art configuration where the incoherent output ASE of an RSOA is simply sliced, without self re-injection. The output power of the transmitter 800 is 1 dBm compared to -21 dBm for the prior art configuration. While it is impossible to achieve any reliable communications with the sliced version (the eye is closed), good performance is achieved with the transmitter 800 of Fig. 8. Fig. 9 also includes the eye diagram measured at -12 dBm for a bit error rate below 10^{-10}. It shows that noise cleaning is indeed effective.

[0064] Fig. 10 shows another SS-WDM transmitter 1000, which is based on the self re-injection of a SOA 1010 using a slicing FBG 1040. The transmitter 1000 uses a SOA 1010 that is directly modulated. One end of the SOA 1010 constitutes its output while the FBG 1040 is connected at its other end. The ASE produced in the SOA 1010 is sliced at the wavelength corresponding to the user channel and is reflected back in the SOA 1010. The resultant is similar to the transmitter 800 of Fig. 8 but the transmitter 1000 is more compact and eliminates the additional insertion loss introduced by the re-injection loop.

[0065] It is noted that the FBG 1040 of Fig. 10 may be replaced by a cascade of a bandpass filters used in transmission and a mirror, the bandpass filter being located between the mirror and the SOA 1010. The latter may be attractive because of its ability to be integrated with all free space optics. The bandpass filters may be made using thin film technology. Another possibility is to design the bandpass thin film filter and the mirror together with the SOA 1010 on the same substrate. This is equivalent to the insertion of a thin film filter between the SOA and the mirror in a standard RSOA.

[0066] Fig. 11 shows an example architecture of a SS-WDM Passive Optical Network (PON) which use the self-reinjected RSOA transmitter 800 of Fig. 8 at the Optical Network Unit (ONU) side and the balanced receiver 100 at the Optical Line Terminal (OLT) side. The architecture also includes an OLT transmitter 1110 on the OLT side and an ONU receiver 1120 on the ONU side, for bi-directional communication. The balanced receiver 100 is made tunable in this case to accommodate various channel wavelengths. Because filtering a noise-cleaned incoherent SS-WDM signal degrades the performance, the remote node consists of passive couplers as standard time-division multiplexed (TDM) PONs **Would you please clarify what you mean by this statement?**. The system of Fig. 11 is compatible with current deployments of single wavelength passive optical networks. There is no need to replace the existing couplers with array-waveguide gratings (AWGs) as for existing WDM and SS-WDM PONs. The OLT receiver 100 should include a multiple and/or tunable version of the balanced receiver 100 of Fig. 1 to exploit the effect of noise cleaning. It is noted that the OLT transmitter 1110 and the ONU receiver 1120 may use any of the suitable configurations described herein. The media access control (MAC) protocol used for time division multiplexing PONs to control the uplink transmission of the different ONUs can be used to tune the filter 32 in the SS-WDM balanced receiver.

[0067] Fig. 12 illustrates an experimental setup of a system architecture using the transmitter 400 of Fig. 4 and the receiver 100 of Fig. 1. In the transmitter 400, a broadband source 410 is sliced into eight channels using an arrayed waveguide gratings 412 with a 30-GHz channel bandwidth and a 100-GHz channel spacing in this case. The power at the input of each noise cleaning device 418 is -8.3 dBm. The noise cleaning devices 418 are fast gain recovery SOAs such as the ones described in W. Mathlouthi, P. Lemieux, L. A. Rusch, “Optimal SOA-based noise reduction schemes for incoherent spectrum-sliced PONs”, IEEE 2006 European Conference on Optical Communication, Cannes, Sept. 2006. It is noted that cascading two SOAs is equivalent to one faster SOA. Two SOAs are thus cascaded for the user channel. A variable attenuator between the two cascaded SOAs sets the input power of the second SOA also at -8.3 dBm, providing a cascade representing a faster SOA, but with unchanged saturation characteristics.

[0068] The user channel (λ_{user}) and adjacent interferer channels (λ_1, λ_3) are individually modulated with a Non-Return-to-Zero (NRZ) PseudoRandom Binary Sequence (PRBS) at several bit rates up to 10 Gbps. To generate additional interferers, four more channels (λ_4, λ_5, λ_6, λ_7) are added. Powers are adjusted so that the average power per channel is the same for all users.

[0069] As discussed herein above, at the balanced receiver 100, the signal coming from the network is first split into two paths 30, 40. The first path 30 of the balanced receiver 100 blocks the desired user signal, i.e., the desired user channel is dropped and all other channels pass through. In this case, the receiver filter 32 is a sinc apodized (first lobe) uniform (over 15 mm) Fiber Bragg Grating (FBG) fabricated with techniques known in the art. The 3-dB bandwidth of the filter 32 is 0.75 nm, and transmission depth is 45 dB. A conventional receiver 1200 is also used alternately with the receiver 100 to provide a reference to which the performance of the balanced receiver 100 is to be compared. The filter 1232 of the conventional receiver 1200 is the same as the filter 32 but used in reflection instead of transmission.

[0070] Fig. 13 shows the Q-factor experimental results as a function of the bit rate for five different transmission system configurations, namely 1) with a single user with no receiver filtering (the ‘*’-solid curve), 2) the balanced receiver 100 (the ‘■’-solid curve), 3) the balanced receiver 100 but with a single SOA as the noise cleaner (the ‘□’-solid curve), 4) the conventional SS-WDM receiver 1200 (the ‘■’-dashed curve) and 5) no noise cleaning (the ‘○’-solid curve). It is noted that the single user curve degrades to the conventional SS-WDM receiver curve if filtering at the receiver is used to isolate one SS-WDM channel. The balanced receiver 100 outperforms the conventional receiver 1200, bridging part of the gap in performance between the conventional receiver 1200 and the single user configuration which has no filtering whatsoever at the receiver. The curve showing the results obtained with the balanced receiver 100 used with a single SOA is also included to confirm that the faster SOA cascade yields better performance.

[0071] Fig. 14 shows the Bit Error Rate (BER) experimental results at 5 Gbps for the setup of Fig. 12 under various loads, namely 1) with a single user, i.e. no interferers (the ‘■’ curves); 2) with two interferers, i.e. the adjacent channels (the ‘●’ curves); and 3) with six interferers (the

'▲' curves). The solid curves denote the use of the balanced receiver 100 while the dashed curves denote the use of the conventional receiver 1200. The balanced receiver shows an error free performance, while the conventional receiver shows bit error rate floors at 10^{-9}. Neither the balanced receiver performance nor the conventional receiver performance is significantly degraded by crosstalk from interferers. It is also noted that no significant power penalty is observed after a propagation over 20 km with the use of a dispersion compensation fiber.

[0072] Fig. 15 compares the performance of both balanced and conventional receivers at 10 Gbps, an important future milestone for access networks and passive optical networks. The balanced receiver 100 results (the '■'-solid curve) are two orders of magnitude better than for the conventional receiver (the '■'-dashed curve). Results obtained with a single user and no receive filtering are also included on the graph (the '■'-solid curve).

[0073] The embodiments of the invention described above are intended to be exemplary only. The scope of the invention is therefore intended to be limited solely by the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A receiver for decoding an optical multiplexed communication signal encoded with a spectral access function associated with an end-user, the receiver comprising:

an optical splitter for receiving the optical multiplexed communication signal carrying data addressed to the end-user and splitting the signal in two signal portions to inputs of two optical paths with substantially equivalent losses and substantially equivalent path lengths, a first one of said optical paths having a filter with a spectral response corresponding to the spectral complement function of said spectral access function, and a second one of said optical paths having an all pass filter; and a balanced photodetector connected between outputs of the two optical paths for detecting a difference between the signal portions propagated in the two optical paths to retrieve the data addressed to the end-user.

2. The receiver as claimed in claim 1, wherein said spectral access function comprises a single wavelength spectrum-sliced function, said communication signal being a spectrum-sliced wavelength division multiplexing signal.

3. The receiver as claimed in claim 2, wherein said single wavelength spectrum-sliced function is tunable in wavelength for said receiver to be set for selecting one of different end-users associated with different specific single wavelength spectrum-slices.

4. The receiver as claimed in claim 1, wherein said spectral access function comprises a spectral amplitude code, said communication signal being a spectral amplitude coded optical code division multiplexing access signal.

5. The receiver as claimed in any one of claims 1 to 4, wherein said all pass filter is a length of optical fiber.

6. The receiver as claimed in any one of claims 1 to 5, wherein said second one of said optical paths comprises a variable attenuator for adjusting the loss of said second one of said optical paths such that the two optical paths have substantially equivalent losses.

7. The receiver as claimed in any one of claims 1 to 6, wherein said filter comprises at least one reflective grating.

8. The receiver as claimed in claim 7, wherein said reflective grating is used in transmission.

9. The receiver as claimed in claim 7 or 8, wherein said reflective grating comprises a fiber Bragg grating.

10. A method for decoding an optical multiplexed communication signal encoded with a spectral access function associated with an end-user, the method comprising:

receiving the optical multiplexed communication signal to be decoded, the signal carrying data addressed to the end-user; splitting the signal into a first portion and a second portion;

filtering said first portion with a spectral complement function of said spectral access code along a first optical path;

propagating said second portion in an unfiltered manner along a second optical path, said first optical path and second optical path having substantially equivalent losses and substantially equivalent path lengths; and detecting a difference between said first portion and said second portion propagated in the first and the second optical paths to retrieve said data addressed to the end-user.

11. The method as claimed in claim 10, wherein said spectral access function comprises a single wavelength spectrum-sliced function and wherein said filtering comprises filtering with the spectral complement function of said single wavelength spectrum-sliced function, for decoding spectrum-sliced wavelength division multiplexing signals.

12. The method as claimed in claim 11, further comprising tuning said single wavelength spectrum-sliced function in wavelength for setting said decoding for use with one of different end-users associated with different specific single wavelength spectrum-slices.

13. The method as claimed in claim 10, wherein said spectral access function comprises a spectral amplitude code and wherein said filtering comprises filtering with the spectral complement function of said spectral amplitude code, for decoding spectral amplitude coded optical code division multiplexing access signals.

14. An optical multiplexed communication system comprising: a transmitter having: an encoder for encoding a broadband light with a spectral access function associated with an end-user; and an electro-optical modulator for modulating the encoded light with data addressed to said end-user to provide an optical multiplexed communication signal, said modulating to be performed after said encoding; and a receiver for decoding the optical multiplexed communication signal, and comprising: an optical splitter for splitting the optical multiplexed communication signal in two signal portions to inputs of two optical paths having substantially equivalent losses and substantially equivalent path lengths, a first one of said optical paths having a filter with a spectral response corresponding to a spectral complement function of said access function, and a second one of said optical paths having an all pass filter; and a balanced photodetector connected between outputs of the two optical paths for detecting a difference between the signal portions propagated in the two optical paths to retrieve said data addressed to the end-user.

15. The system as claimed in claim 14, wherein said spectral access function comprises a single wavelength spectrum-sliced function, said communication signal being a spectrum-

sliced wavelength division multiplexing signal.

16. The system as claimed in claim 14, wherein said spectral access function comprises a spectral amplitude code, said communication signal being a spectral amplitude coded optical code division multiplexing access signal.

17. The system as claimed in claim 16, wherein said encoder comprises a cascade of reflective gratings used in reflection, and wherein said filter comprises an equivalent one of said cascade used in transmission.

18. The system as claimed in claim 17, wherein said cascade of reflective gratings comprises a fiber Bragg grating.

19. The system as claimed in any one of claims 14 to 18, wherein said transmitter further comprises an optical amplifier for substantially suppressing noise on said optical multiplexed communication signal.

20. The system as claimed in claim 19, wherein said optical amplifier is located between said encoder and said modulator.

21. The system as claimed in claim 19, wherein said optical amplifier comprises a semiconductor optical amplifier.

22. The system as claimed in claim 19, wherein said optical amplifier comprises a hybrid evanescent optical amplifier.

23. The system as claimed in claim 22, wherein the transmitter is all integrated onto a single silicon photonic chip.

24. The system as claimed in any one of claims 14 to 23, further comprising an incoherent broadband light source for providing said broadband light.

25. The system as claimed in any one of claims 16 to 18, further comprising a coherent broadband light source for providing said broadband light.

26. An Optical Code Division Multiplexing Access (OCDMA) transmitter, the transmitter comprising:

    an OCDMA encoder for encoding a broadband light with an access code associated with an end-user; and an electro-optical modulator receiving the encoded broadband light for modulating the encoded light with data addressed to said end-user to provide an OCDMA signal; wherein said modulation is performed after the OCDMA encoding.

27. The transmitter as claimed in claim 26, further comprising an optical amplifier for substantially suppressing noise on said OCDMA signal.

28. The transmitter as claimed in claim 27, wherein said optical amplifier is located between said encoder and said modulator.

29. The transmitter as claimed in claim 27 or 28, wherein said optical amplifier comprises a semiconductor optical amplifier.

30. The transmitter as claimed in claim 27 or 28, wherein said optical amplifier comprises a hybrid evanescent optical amplifier.

31. The transmitter as claimed in any one of claims 26 to 30, wherein said OCDMA encoder comprises a cascade of reflective gratings used in reflection, said OCDMA transmitter being based on spectral amplitude coded OCDMA.

32. The transmitter as claimed in claim 31, wherein said cascade of reflective gratings comprises a fiber Bragg grating.

33. The system as claimed in any one of claims 25 to 31, further comprising an incoherent broadband light source for providing said broadband light.

34. A spectral amplitude coded Optical Code Division Multiplexing Access (OCDMA) system comprising: a transmitter having an OCDMA encoder for encoding an OCDMA signal with a spectral access code associated with an end-user, said encoder comprising a multi-wavelength reflective grating used in reflection; and a balanced receiver for decoding the OCDMA signal and having two optical paths with substantially equivalent losses and path lengths, a first one of said optical paths having a filter comprising an equivalent one of said cascade used in transmission to provide a spectral complement function of said spectral access code.

35. The system as claimed in claim 34, wherein the multi-wavelength reflective grating comprises a fiber Bragg grating.

36. An optical multiplexed communication system comprising: a transmitter source for generating an optical multiplexed communication signal encoded with a spectral access function associated with an end-user, the transmitter source having: an optical amplifier modulated with data addressed to the end-user and generating amplified spontaneous emission, and an encoding filter having a spectral response corresponding to said spectral access function, and connected to the optical amplifier so as to filter the amplified spontaneous emission according to said spectral response and re-inject it back in the optical amplifier in order to saturate the optical amplifier and generate the optical multiplexed communication signal encoded with the spectral access function; and a receiver for decoding the optical multiplexed communication signal, and comprising: an optical splitter for splitting the optical multiplexed communication signal in two signal portions to inputs of two optical paths having substantially equivalent losses and substantially equivalent path lengths, a first one of said optical paths having a filter with a spectral response corresponding to a spectra complement function of said access function, and a second one of said optical paths having an all pass filter; and a balanced

photodetector connected between outputs of the two optical paths for detecting a difference between the signal portions propagated in the two optical paths to retrieve said data addressed to the end-user.

37. The system as claimed in claim 36, wherein the optical amplifier comprises a reflective semiconductor optical amplifier, and wherein the transmitter source further comprises an optical splitter to split the light signal exiting the optical amplifier into a first portion comprising the generated optical multiplexed communication signal and a second portion, the second portion being filtered by the encoding filter and re-injected back in the optical amplifier.

38. The system as claimed in claim 36, wherein the optical amplifier has a first and a second end, and wherein said encoding filter comprises a reflective grating used in reflection and connected to the first end of the optical amplifier such that amplified spontaneous emission reflected by the reflective grating is re-injected back in the optical amplifier, the generated optical multiplexed communication signal exiting the optical amplifier by the second end.

<u>ABSTRACT</u>

There is provided improved transceivers for both Spectrum Sliced Wavelength Division Multiplexing (SS-WDM) and incoherent Optical Code Division Multiplexing Access (OCDMA) systems, and capable of enhancing the quality of the received signal before photo-detection. A balanced receiver design cancels the intra-channel crosstalk as well as the additive amplified spontaneous emission (ASE) noise in the amplified SS-WDM case. The combination of the optical amplifier transmitter and balanced receiver reduces excess intensity noise (also called beat noise and phase induced intensity noise) in the case of both WDM and OCDMA systems with optical incoherent broadband sources and also in the case of OCDMA systems using coherent sources.

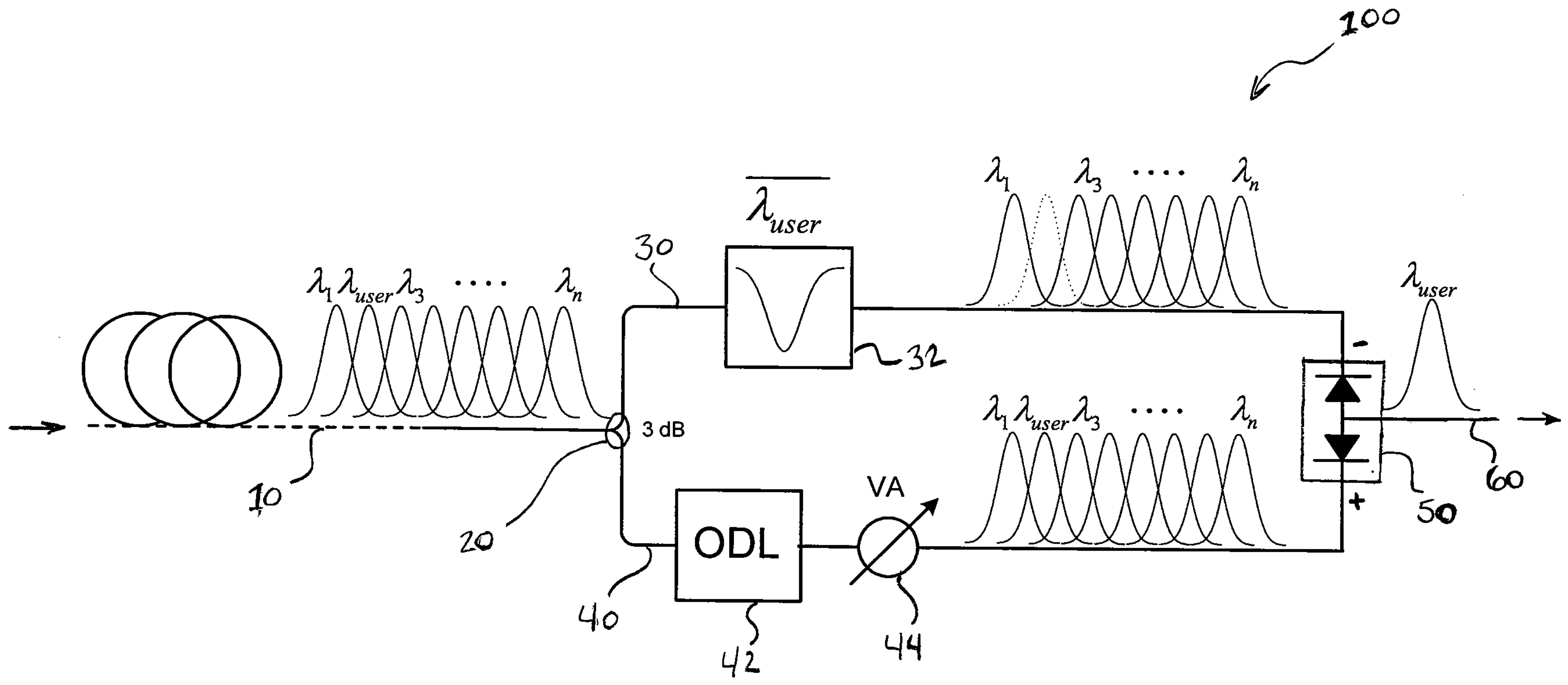

100
λ_1 λ_{user} λ_3 .... λ_n
$\overline{\lambda_{user}}$
λ_1 λ_3 .... λ_n
λ_{user}
30
32
3 dB
10
20
-
+
50
60
λ_1 λ_{user} λ_3 .... λ_n
VA
ODL
40
42
44

Fig. 1

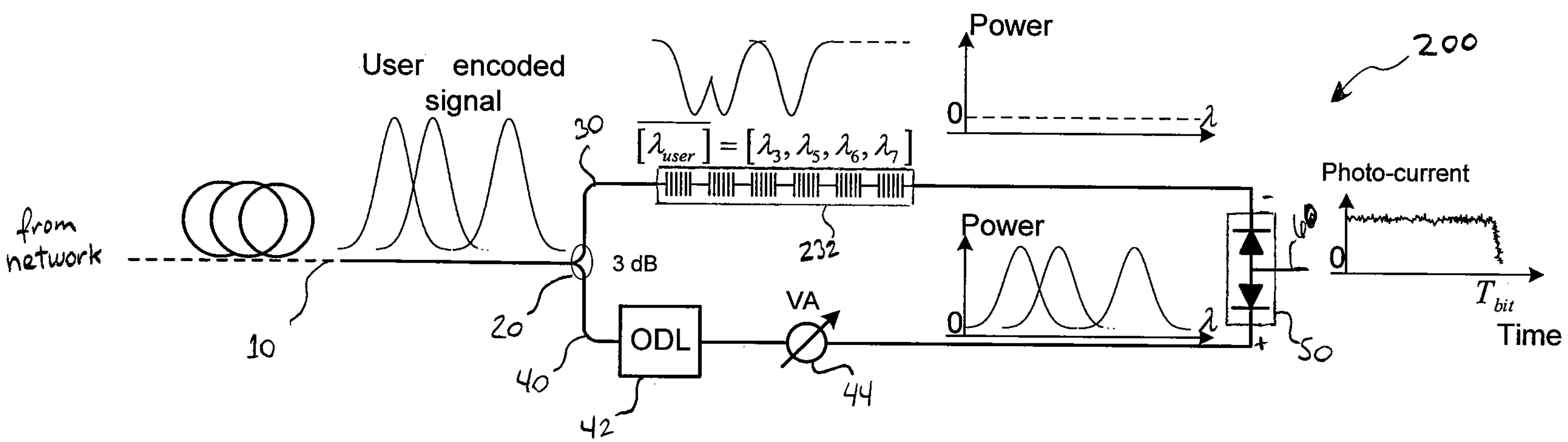

200
User encoded signal
from network
10
20
3 dB
30
40
42
ODL
VA
44
$\overline{[\lambda_{user}]} = [\lambda_3, \lambda_5, \lambda_6, \lambda_7]$
232
Power
0
λ
Power
0
λ
-
+
60
50
Photo-current
0
T_{bit}
Time

Fig. 2A

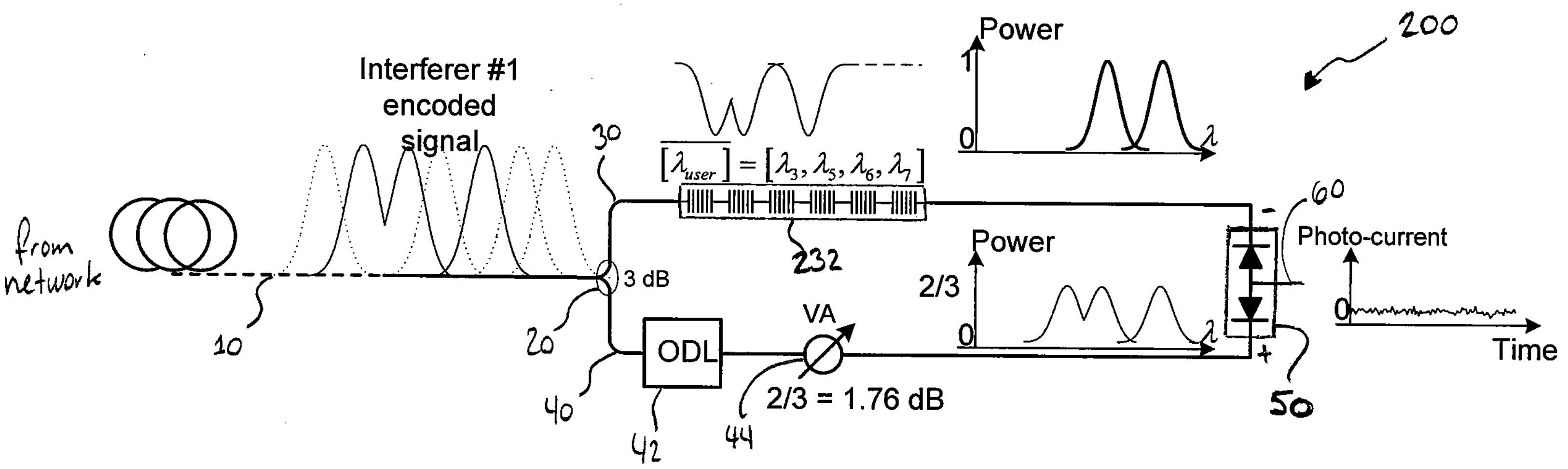

200
Interferer #1 encoded signal
from network
10
20
3 dB
30
40
42
ODL
VA
44
2/3 = 1.76 dB
$\overline{[\lambda_{user}]} = [\lambda_3, \lambda_5, \lambda_6, \lambda_7]$
232
Power
1
0
λ
Power
2/3
0
λ
-
+
60
50
Photo-current
0
Time

Fig. 2B

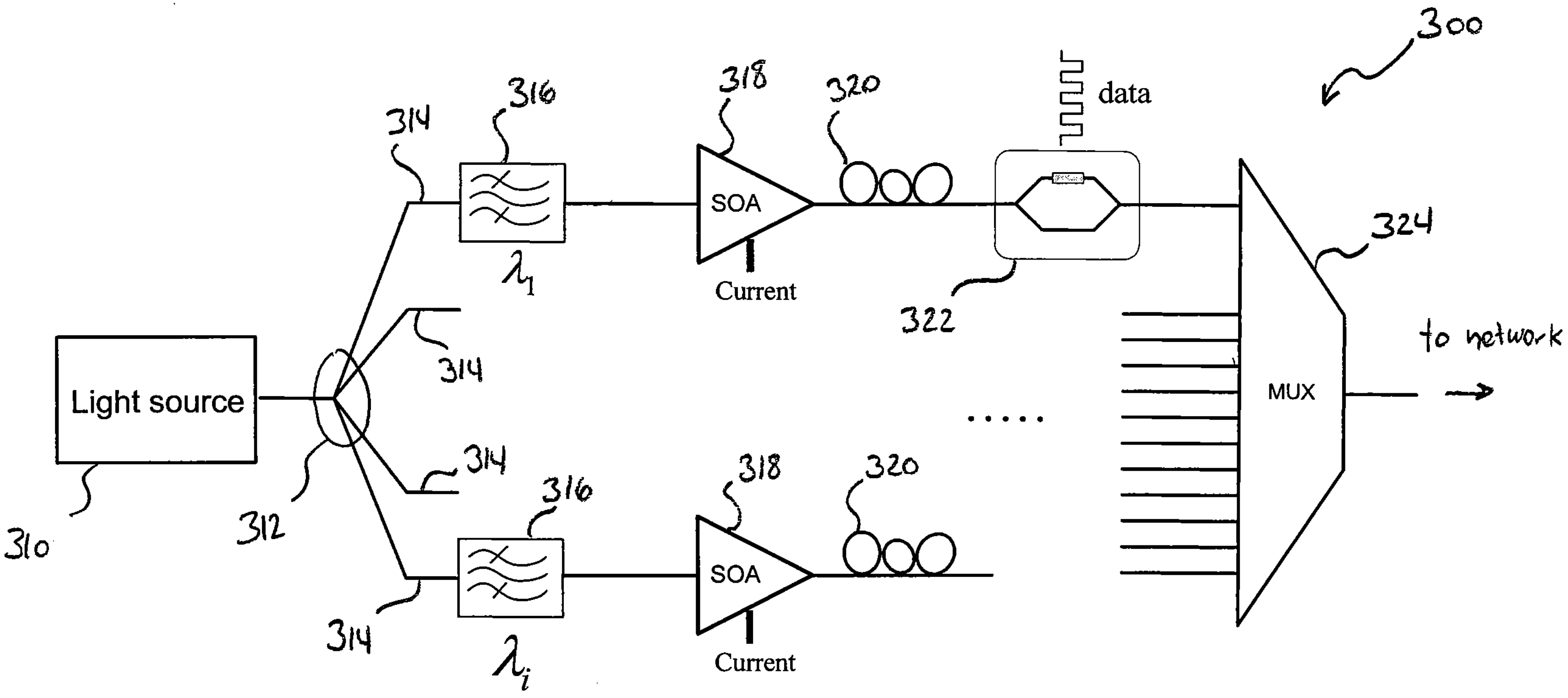

300
Light source
310
312
314
314
314
314
316
316
λ_1
λ_i
318
318
SOA
SOA
Current
Current
320
320
data
322
.....
324
MUX
to network

Fig. 3

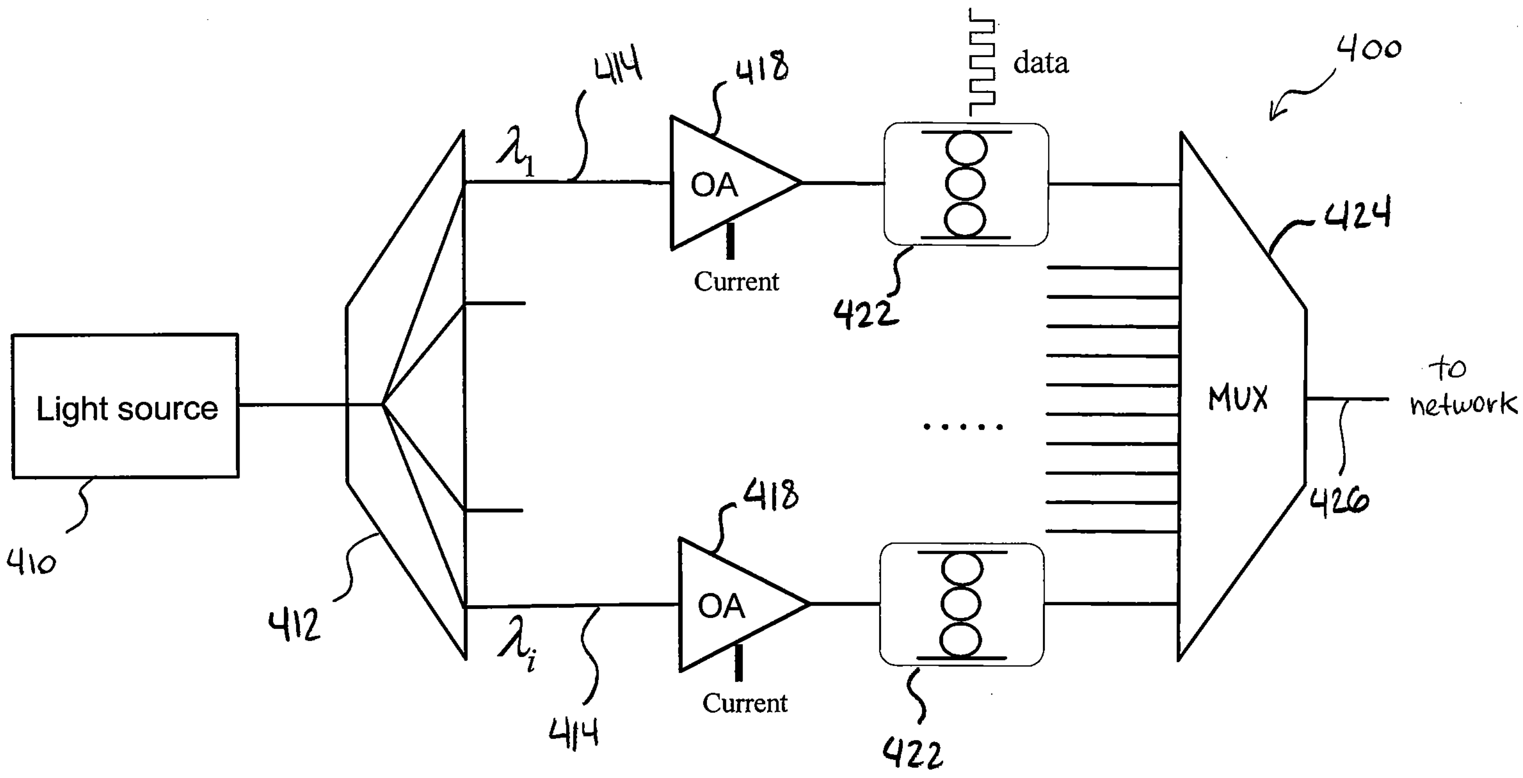

400
Light source
410
412
λ_1
λ_i
414
414
418
418
OA
OA
Current
Current
data
422
422
MUX
424
426
to network

FIG. 4

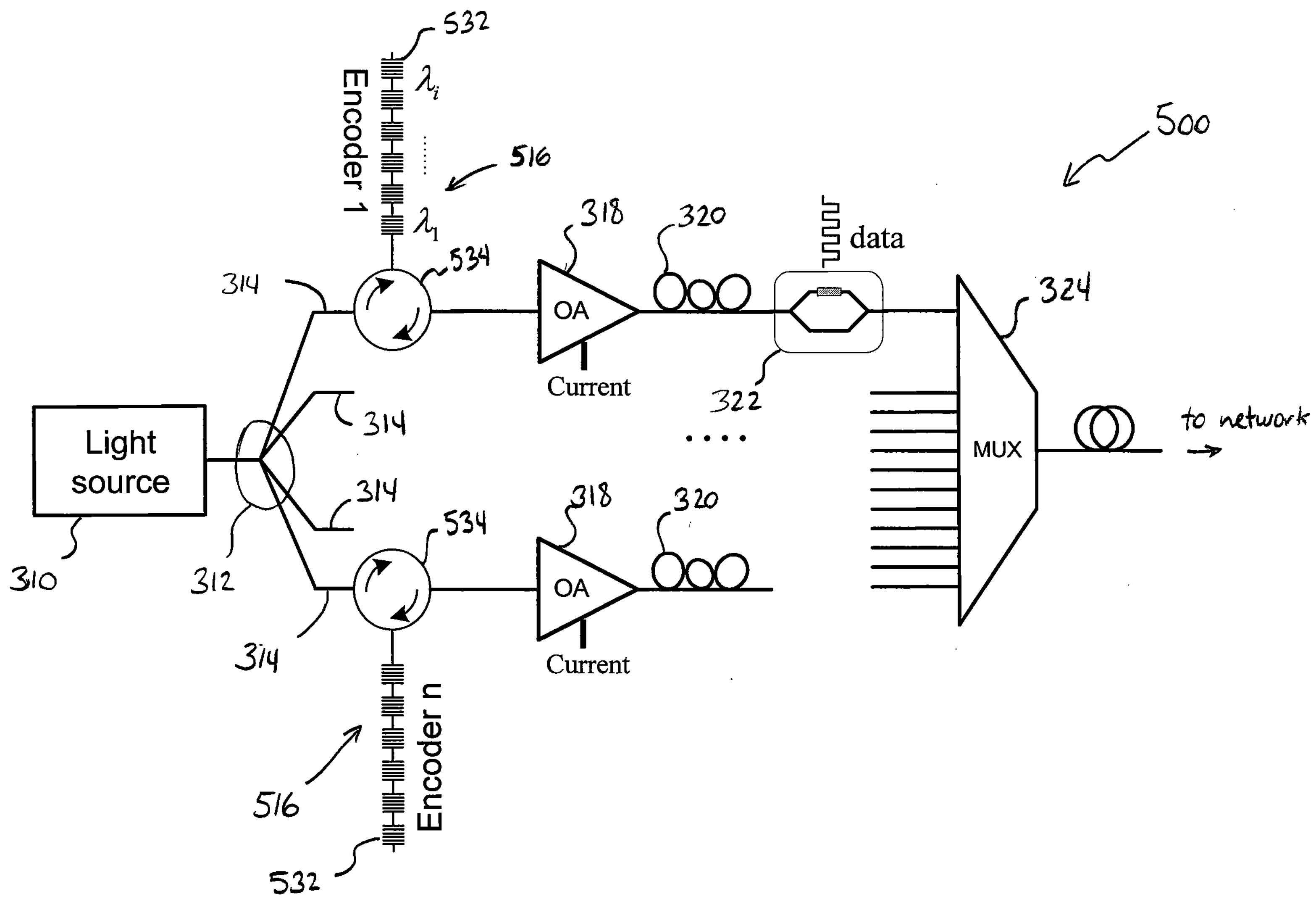

500
532
Encoder 1
λ_i
516
λ_1
534
314
318
320
data
324
OA
Current
322
Light source
314
314
MUX
to network
310
312
534
318
320
OA
314
Current
516
Encoder n
532

Fig. 5

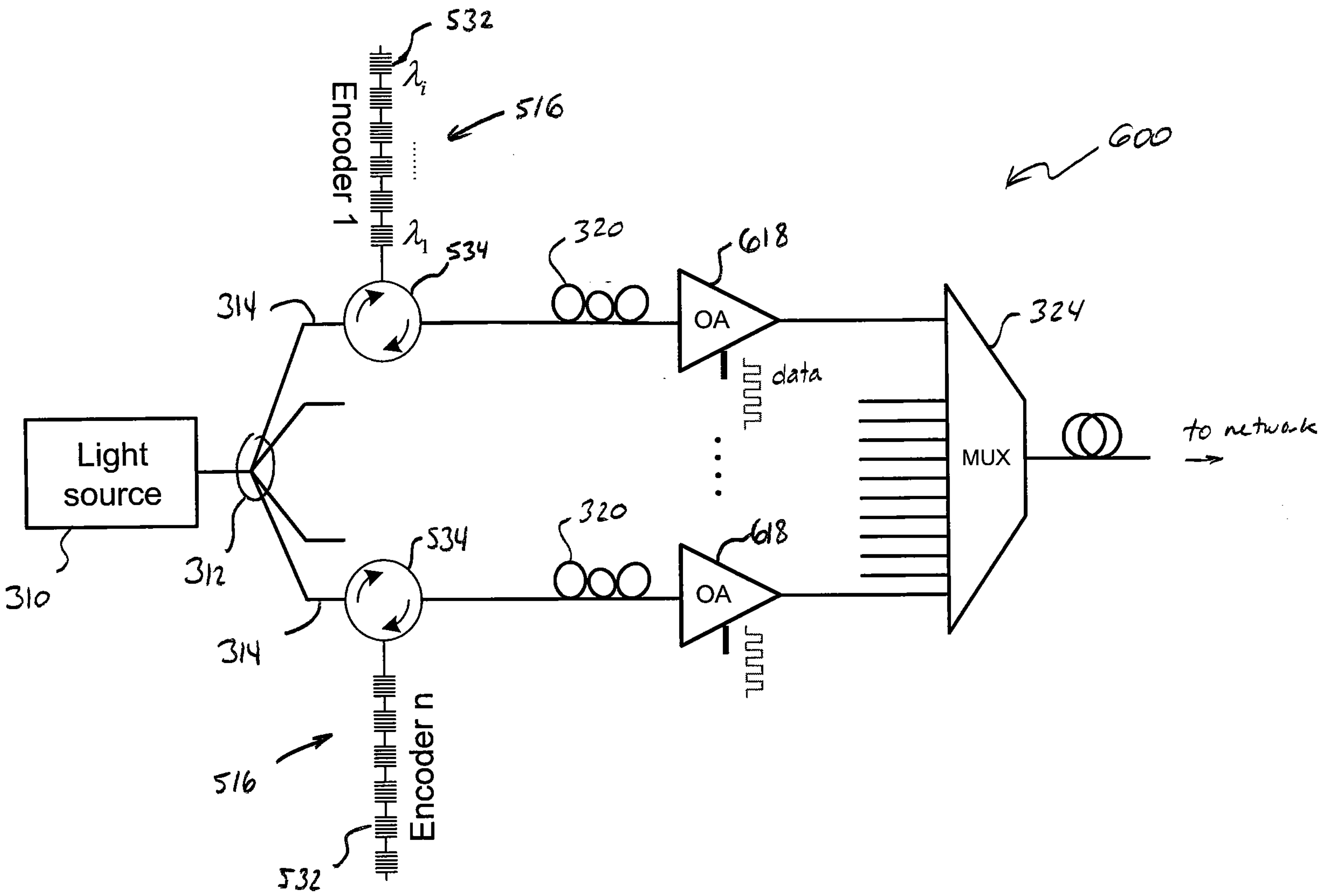

600
532
λ_i
516
Encoder 1
......
λ_1
534
320
618
314
OA
data
324
Light source
MUX
to network
310
312
320
534
618
OA
314
516
Encoder n
532

FIG. 6

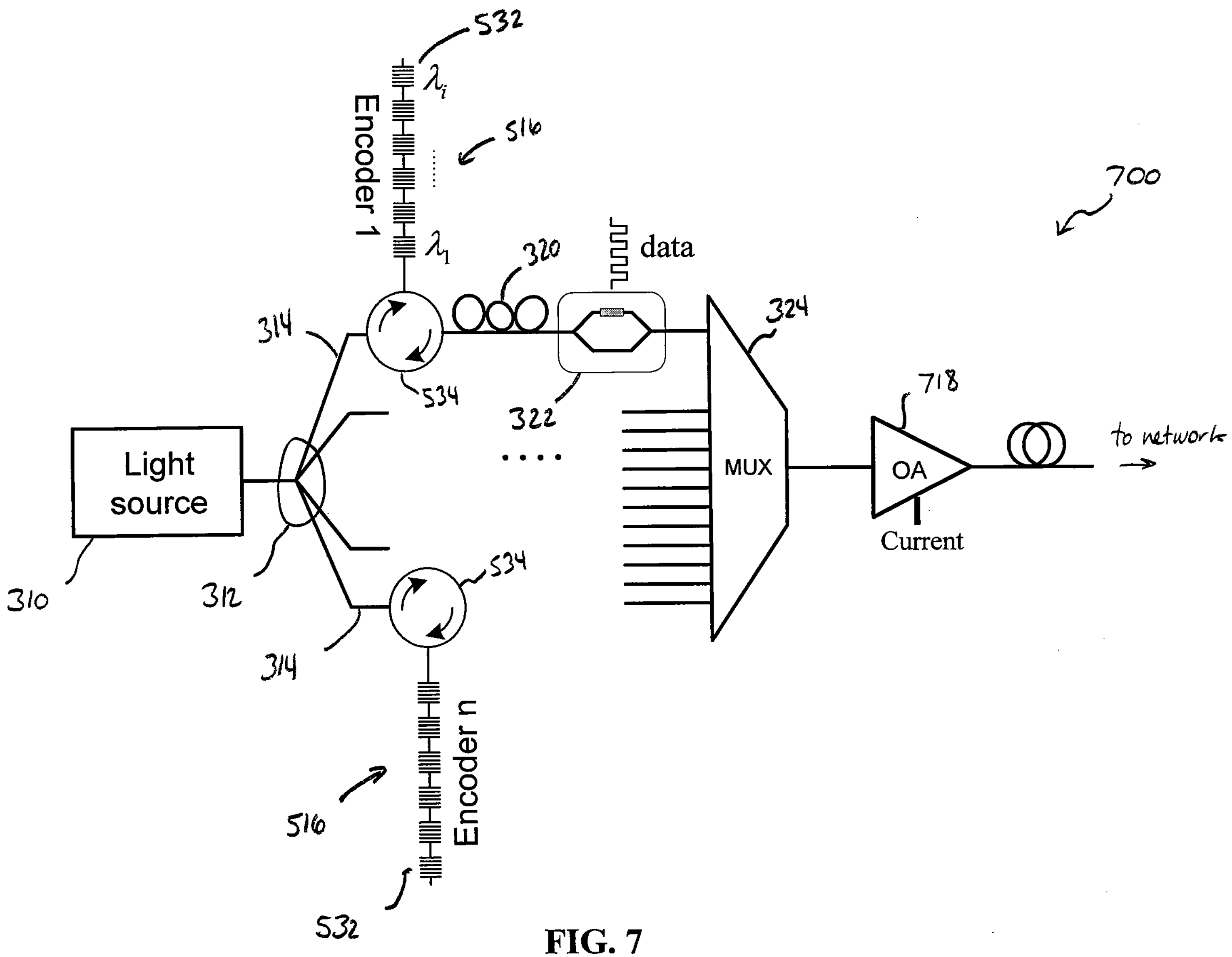
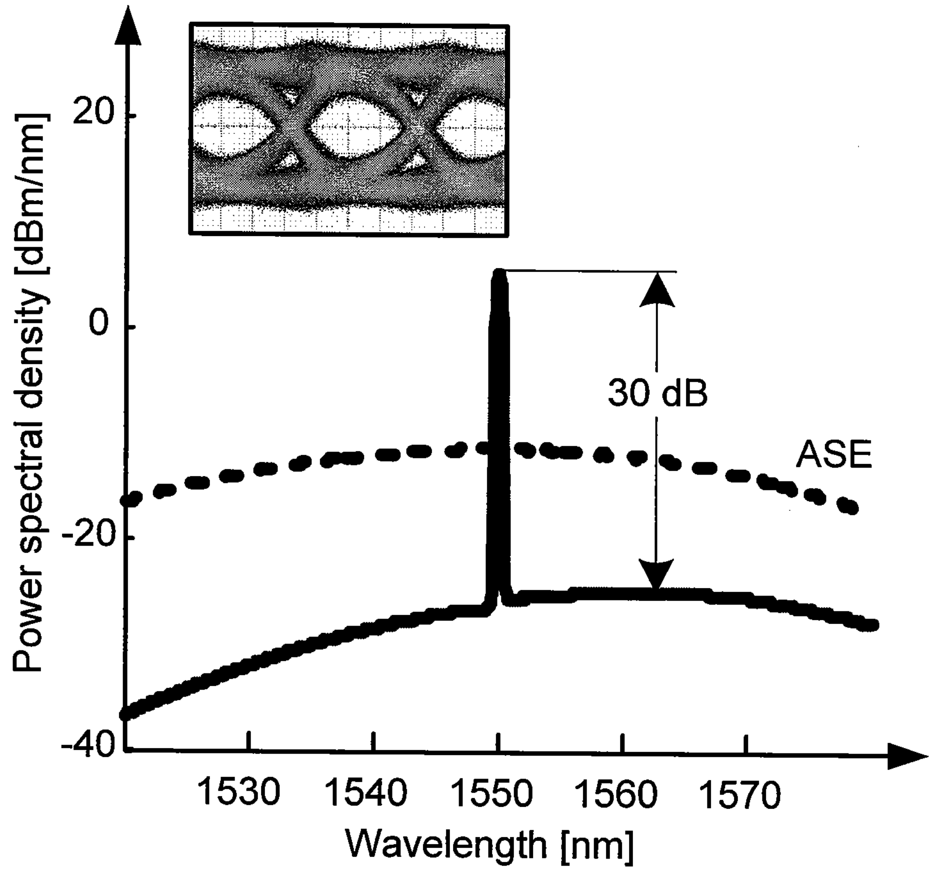

532
516
700
Encoder 1
λ_i
λ_1
320
data
314
324
534
322
718
Light source
MUX
OA
to network
310
312
534
Current
314
Encoder n
516
532

FIG. 7



Power spectral density [dBm/nm]
20
0
-20
-40
30 dB
ASE
1530
1540
1550
1560
1570
Wavelength [nm]

Fig. 9

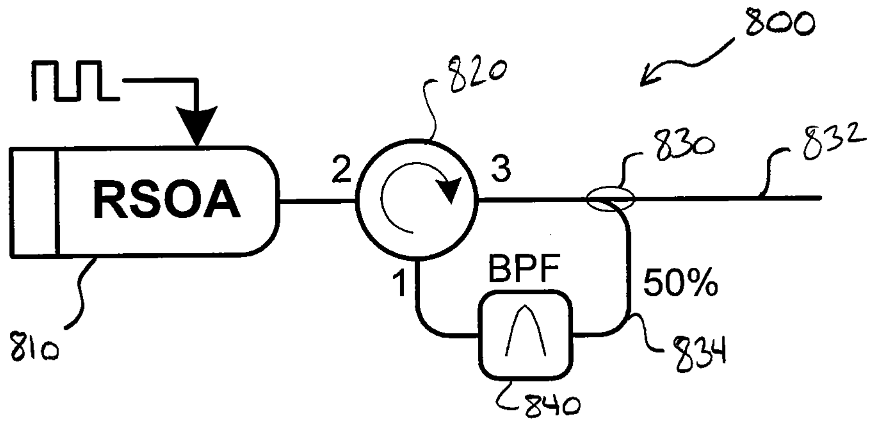

800
820
RSOA
2
3
830
832
1
BPF
50%
810
834
840

Fig. 8

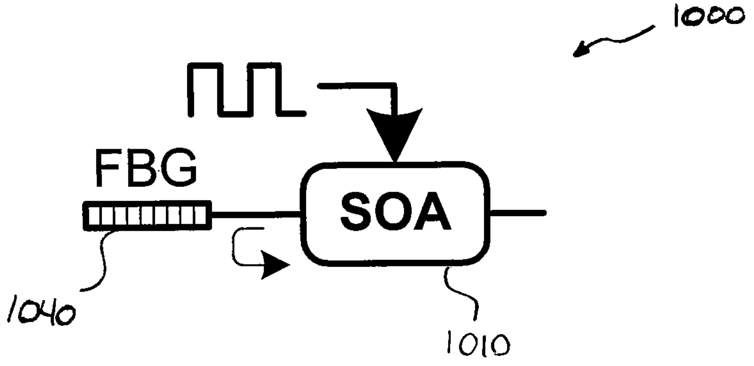

1000
FBG
SOA
1040
1010

Fig. 10

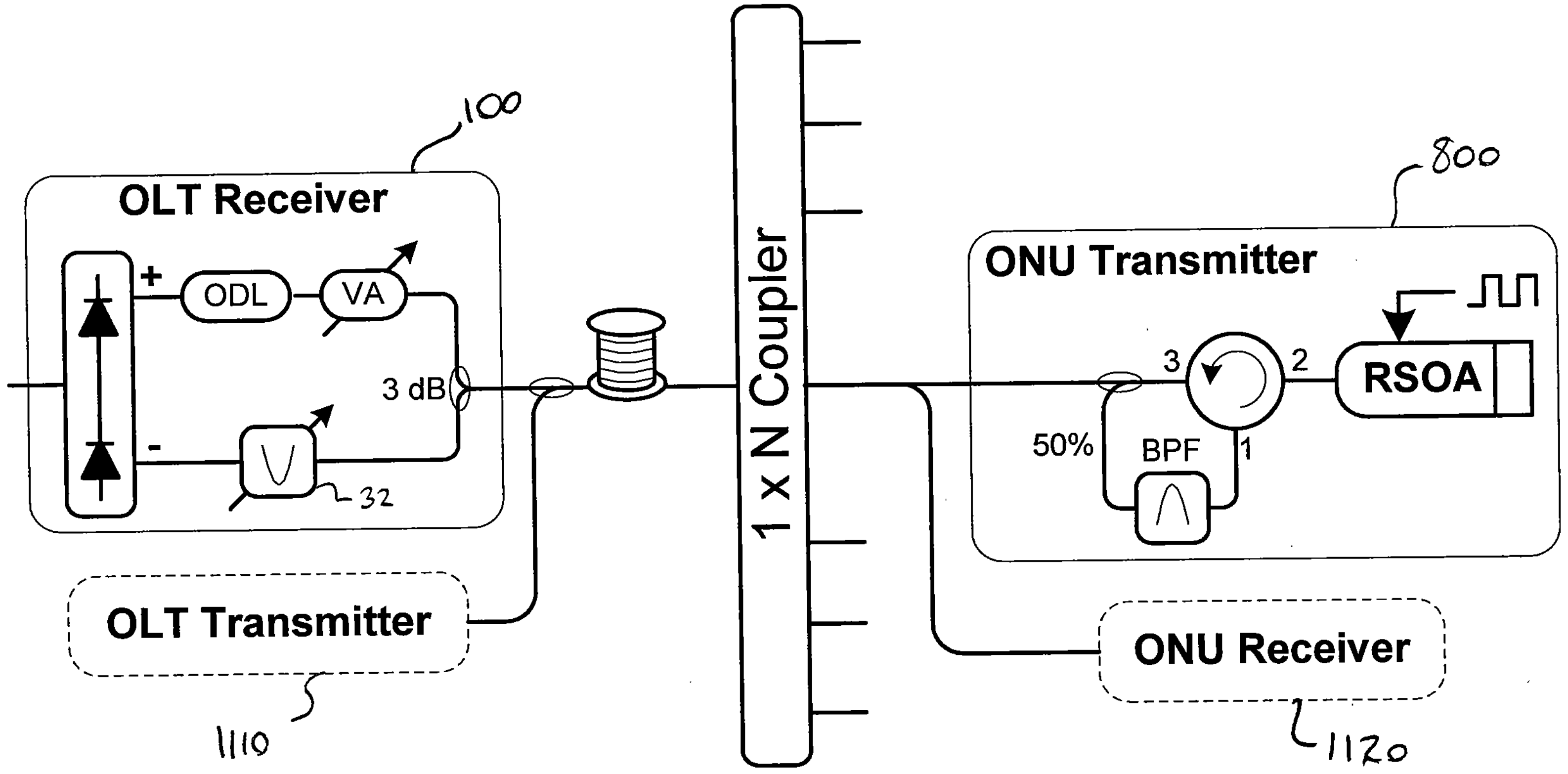
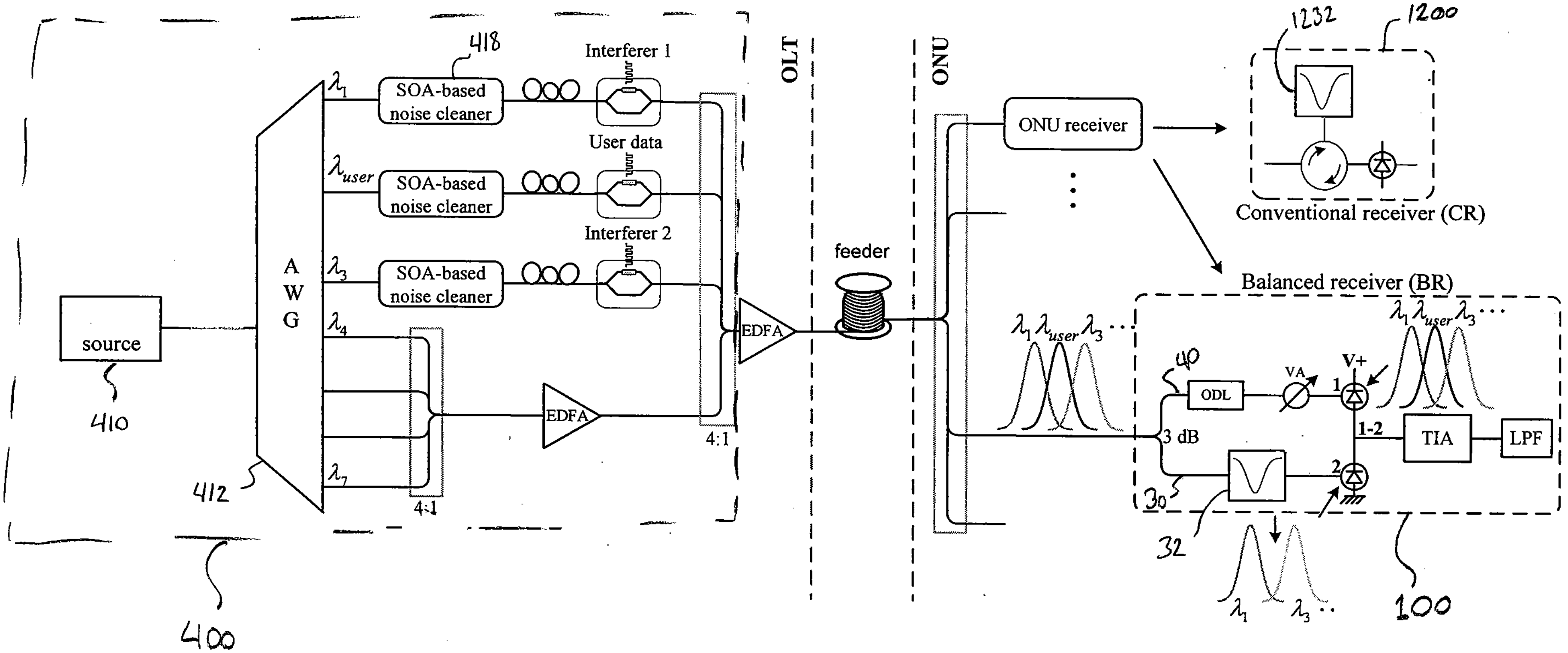

100
OLT Receiver
+
ODL
VA
3 dB
-
32
OLT Transmitter
1110
1 x N Coupler
800
ONU Transmitter
RSOA
3
2
50%
BPF
1
ONU Receiver
1120

Fig. 11



1232
1200
418
Interferer 1
OLT
ONU
ONU receiver
Conventional receiver (CR)
λ_1
SOA-based noise cleaner
λ_{user}
User data
SOA-based noise cleaner
Interferer 2
λ_3
SOA-based noise cleaner
A W G
feeder
Balanced receiver (BR)
source
λ_4
EDFA
EDFA
$\lambda_1 \lambda_{user} \lambda_3 \cdots$
$\lambda_1 \lambda_{user} \lambda_3 \cdots$
40
ODL
VA
V+
1
3 dB
1-2
TIA
LPF
410
412
λ_7
4:1
4:1
2
30
32
λ_1
$\lambda_3 \cdots$
100
400

Fig. 12

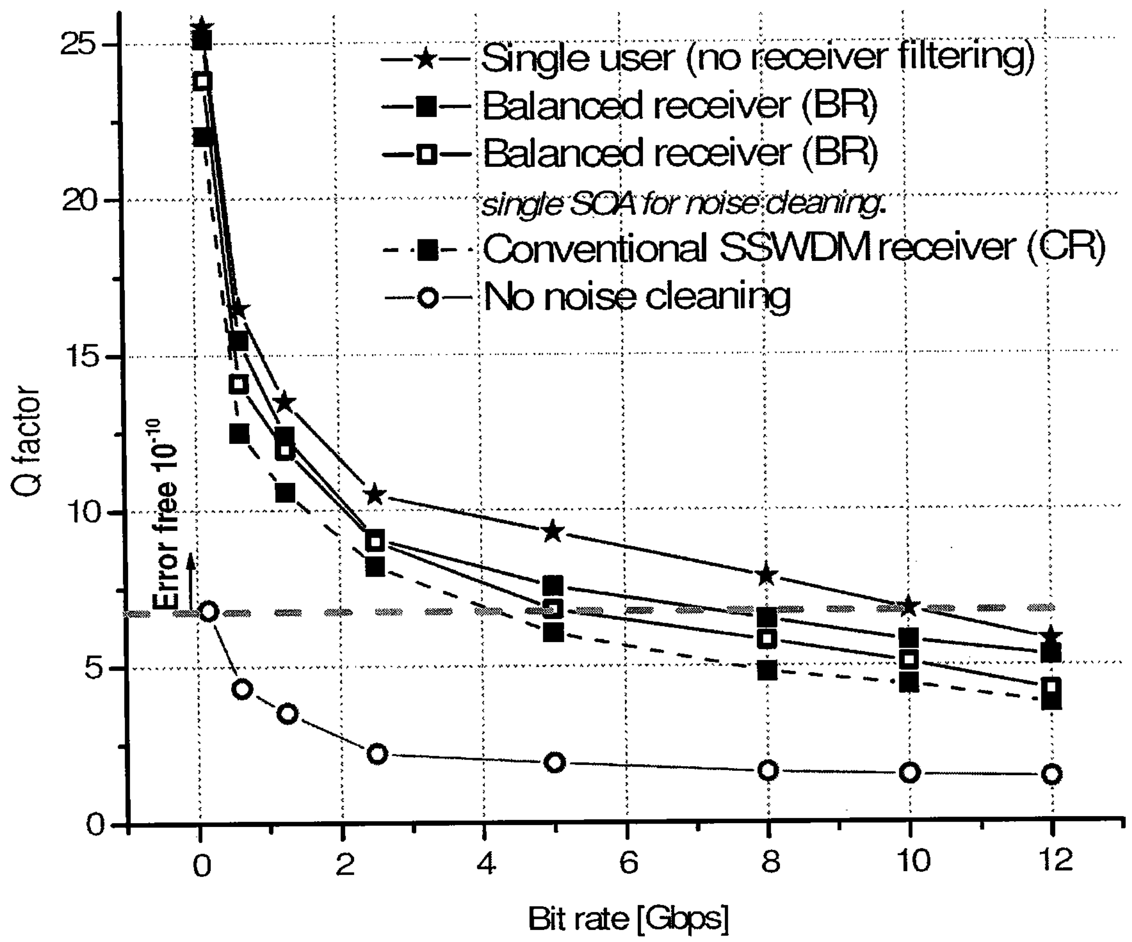

Single user (no receiver filtering)
Balanced receiver (BR)
Balanced receiver (BR)
single SOA for noise cleaning.
Conventional SSWDM receiver (CR)
No noise cleaning
Q factor
Error free 10^{-10}
0
5
10
15
20
25
0
2
4
6
8
10
12
Bit rate [Gbps]

FIG. 13

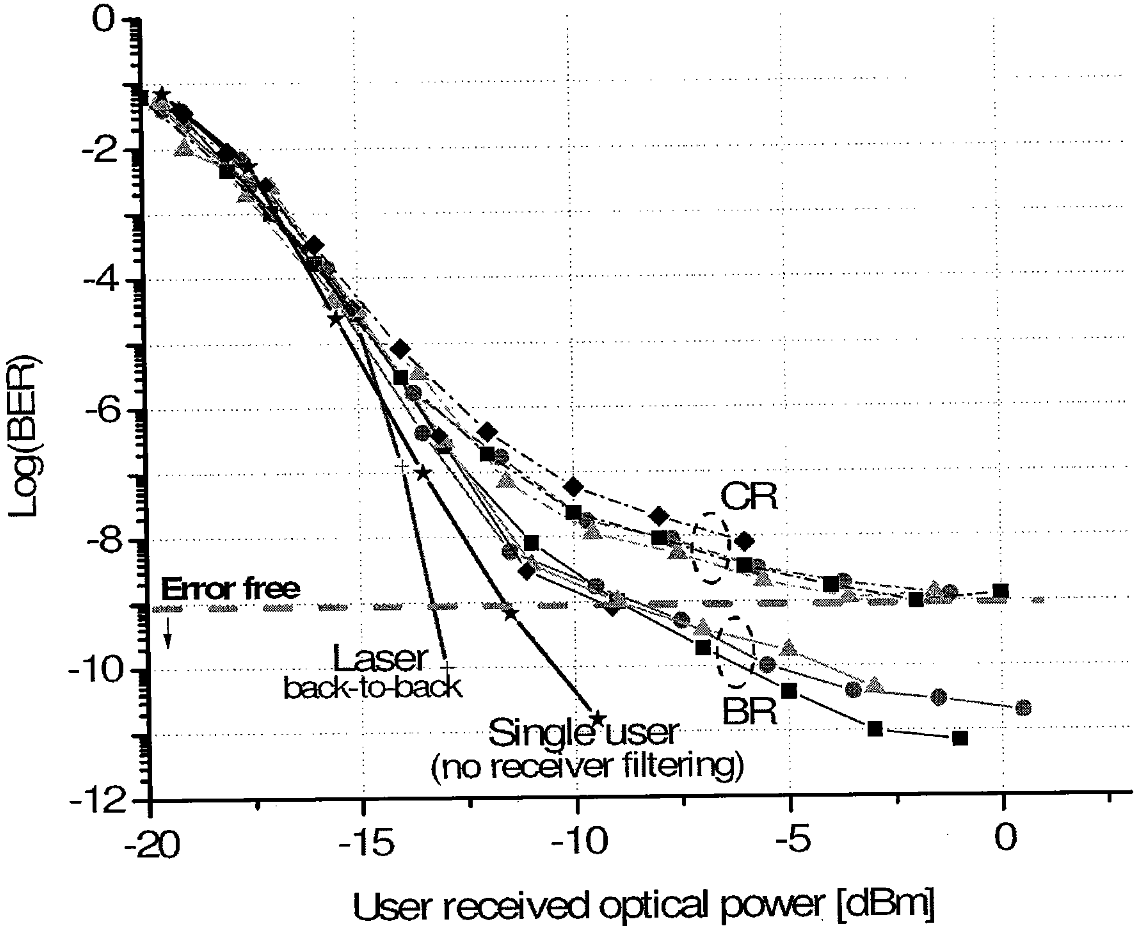

0
-2
-4
-6
-8
-10
-12
Log(BER)
-20
-15
-10
-5
0
User received optical power [dBm]
Error free
Laser
back-to-back
Single user
(no receiver filtering)
CR
BR

FIG. 14

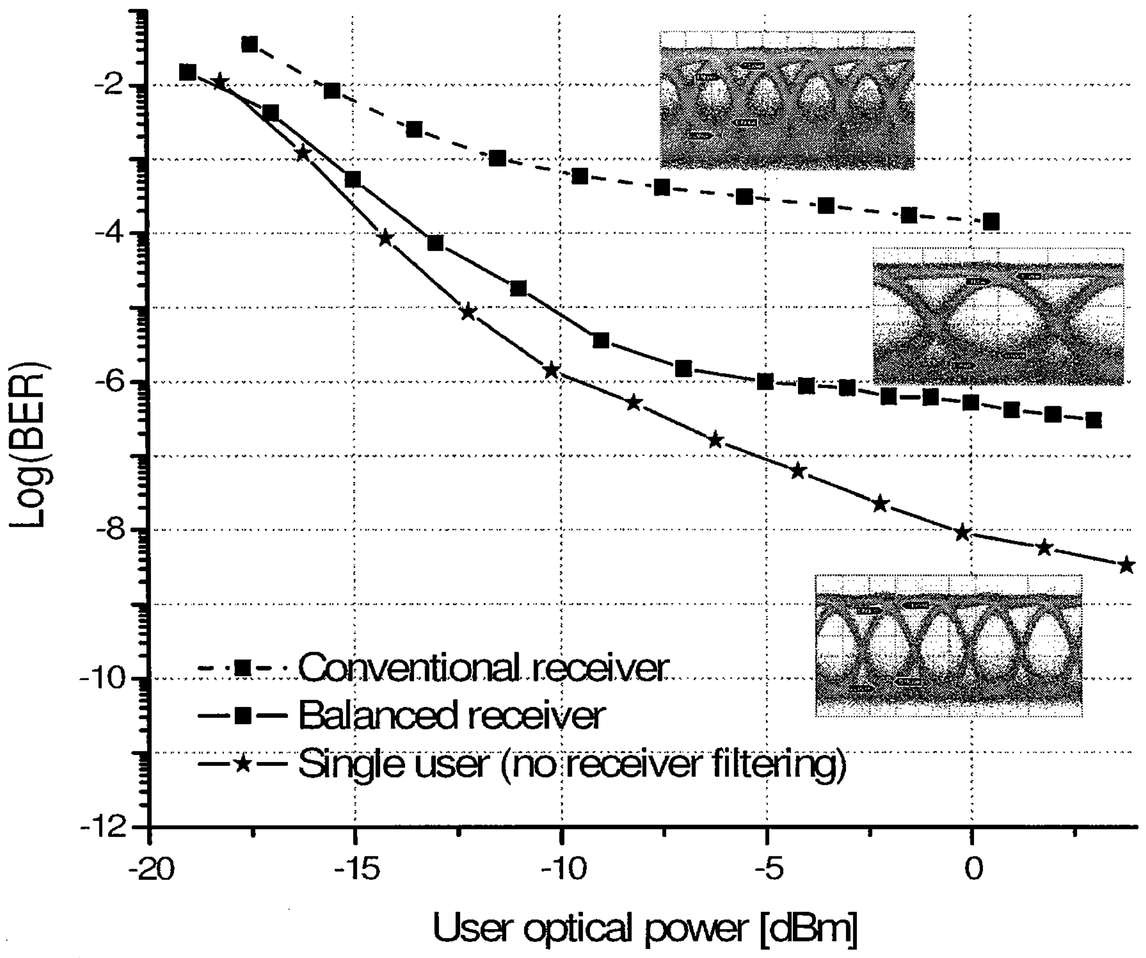

Log(BER)
-2
-4
-6
-8
-10
-12
-20
-15
-10
-5
0
User optical power [dBm]
Conventional receiver
Balanced receiver
Single user (no receiver filtering)

FIG. 15