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Dual sensing opto-electronic receiver

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(71) Applicant(s)
Curtin University of Technology

(72) Inventor(s)
Roy Howard

(74) Agent/Attorney
GRIFFITH HACK,256 Adelaide Terrace,PERTH WA 6000

(56) Related Art
US 6414769

ABSTRACT

A dual sensing opto-electronic receiver is described with improved noise performance to the extent that the input equivalent noise power spectral density is halved or, equivalently, the output signal to noise ratio is double. The dual sensing receiver includes a photodetector (10) for generating an electrical signal in response to incident radiation and having first and second terminals. A first amplifier 12 is connected to the first terminal for sensing the electrical signal and producing a first output signal and a second amplifier (14) is connected to the second terminal for sensing the electrical signal and producing a second output signal. A summa is connected to the output of said first and second amplifiers (12,14) and subtracts the first and second output signals to produce the receiver output. The improved noise performance of the opto-electronic receiver is achieved by sensing the photodetector signal current at both terminals.

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Regulation 3.2

AUSTRALIA

PATENTS ACT 1990

COMPLETE SPECIFICATION FOR A STANDARD PATENT

Name of Applicant:	CURTIN UNIVERSITY OF TECHNOLOGY
Address of Applicant:	Kent Street Bentley, Western Australia 6102 Australia
Actual Inventor:	Dr. Roy HOWARD
Address for Service:	Griffith Hack, Patent and Trade Mark Attorneys, 6th Floor, 256 Adelaide Terrace, Perth, Western Australia, 6000.

Standard Complete Specification for the invention entitled:

DUAL SENSING OPTO-ELECTRONIC RECEIVER

Details of Associated Provisional Applications:

PP2445 filed in Australia on 18 March 1998

The following is a full description of this invention, including the best method of performing it known to me:-

DUAL SENSING OPTO-ELECTRONIC RECEIVER

FIELD OF THE INVENTION

The present invention relates to a dual sensing opto-electronic receiver and relates particularly, though not exclusively, to a dual sensing opto-electronic receiver in which the input noise can be significantly reduced, with a value approaching half the input equivalent noise level of a standard opto-electronic receiver being attainable.

BACKGROUND TO THE INVENTION

An opto-electronic receiver is an essential component of any system requiring optical to electrical conversion of a signal or signals. Hence, opto-electronic receivers are found in a diverse range of systems including thermal imaging systems, instrumentation systems based on optical fibre sensors, and optical fibre based communication systems. It is often the case that the performance of a system incorporating an opto-electronic receiver is determined by the level of noise introduced by the receiver. Accordingly, if the level of noise in an opto-electronic receiver can be reduced then a higher level of performance can be achieved. For example, in a thermal imaging system a lower opto-electronic receiver noise level results in the possibility of detecting signals of lower intensity. Again, for example, in optical fibre communication systems the opto-electronic receiver noise level determines the maximum distance a signal can be transmitted, and a specified level of system performance maintained, before either an optical amplifier or a standard opto-electronic repeater has to be used. This follows because, as with all physical media, optical fibres have loss, and as a consequence, the signal level in an optical fibre cable decays with distance. Ultimately, the signal would become smaller than the noise level of an opto-electronic receiver and, hence, not be detectable. For short distance optical communication systems a lower opto-electronic receiver noise level results in less transmitted optical power being required to maintain a specified level of performance.

SUMMARY OF THE INVENTION

The present invention was developed with a view to providing a dual sensing opto-electronic receiver with improved noise performance over that of a standard opto-electronic receiver. The improved noise performance attainable is consistent with a level approaching half the input equivalent noise level, or double the signal to noise ratio, of a standard receiver.

According to the present invention there is provided a dual sensing opto-electronic receiver comprising:

a photodetector for generating an electrical signal in response to incident radiation and having first and second terminals;

an amplifying means connected to both said first and second terminals for sensing said electrical signal whereby, in use, the input equivalent noise of the receiver is substantially reduced.

Advantageously said amplifying means comprises a first amplifier connected to said first terminal for sensing said electrical signal and producing a first output signal; and,

a second amplifier connected to said second terminal for sensing said electrical signal and producing a second output signal.

Preferably the dual sensing opto-electronic receiver further comprises:

combining means operatively connected to said first and second amplifiers for combining said first and second output signals.

Typically said photodetector is a photodiode.

Preferably the magnitude of the photodiode impedance is large in comparison with the magnitude of the input impedance of the following amplifiers, the photodetector noise is less than the input equivalent noise of the following amplifiers, and the dominant amplifier noise source occurs at the amplifier input. When these preferable, but not exclusive, conditions hold the input equivalent noise of a dual sensing opto-electronic receiver approaches a value which is half that of a corresponding standard receiver. This level of performance is consistent with a signal to noise ratio of a dual sensing receiver approaching a value which is double that of a standard receiver.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to facilitate a more comprehensive understanding of the invention possible embodiments of the dual sensing opto-electronic receiver will now be described in detail, by way of example only, with reference to the accompanying drawings, in which:

Figure 1(a), (b) and (c) illustrate schematically prior art standard opto-electronic receivers;

Figure 2 illustrates schematically one embodiment of a dual sensing opto-electronic receiver in accordance with the invention;

Figure 3(a) illustrates schematically the standard opto-electronic receiver of Figure 1(c) in which a standard model of a photodiode is used;

Figure 3(b) illustrates schematically the dual sensing opto-electronic receiver of Figure 2 based on the standard receiver illustrated in Figure 3(a);

Figure 4 is a graphical representation of the ratio of the signal to noise ratio of a dual sensing receiver to the signal to noise ratio of a standard receiver as a function of the ratio of the photodetector noise to amplifier noise;

Figure 5 illustrates schematically an example of a standard JFET based transimpedance receiver;

Figure 6 illustrates schematically a dual sensing receiver based on the transimpedance amplifier shown in Figure 5;

Figure 7 is a graphical representation of the normalised output noise power spectral density of the dual sensing receiver shown in Figure 6 (lower trace) and the standard receiver shown in Figure 5 (upper trace); and,

Figure 8 illustrates schematically an alternative embodiment of a dual sensing receiver in accordance with the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Figure 1 illustrates three different forms of standard prior art opto-electronic receivers. Figure 1(a) is a standard transimpedance amplifier and Figure 1(b) is a standard high impedance front end receiver. Both are driven by a standard photodetector 10, for example, an Si p-i-n photodiode, or an InGaAs APD. In either of these receivers the goal is to provide an appropriate transimpedance transfer function between the photodetector signal current, $i_s(t)$, and the voltage required for subsequent processing circuitry. If the receiver output voltage is $v_o(t)$ then the achieved transimpedance transfer function, $T(s)$, is:

$$T(s) = \frac{V_o(s)}{I_s(S)} \qquad (1)$$

where $V_o(s)$ and $I_s(s)$, respectively, are the Laplace Transforms of $i_s(t)$ and $v_o(t)$. For the purposes of analysis, it is convenient to incorporate the bias resistor R_b of the high impedance front end, the feedback resistor R_f of the transimpedance amplifier, and the amplifier load impedance Z_l into the amplifier model to produce an augmented amplifier 12, as shown in the general opto-electronic receiver model illustrated in Figure 1(c).

As is evident from Figure 1, a standard opto-electronic receiver only senses the signal current, $i_s(t)$, generated by the photodetector 10 in response incident radiation, at one of its terminals.

The present invention is based on the discovery that if the photodetector signal current is sensed at both terminals, as illustrated in Figure 2, it is possible to improve the opto-electronic receiver noise performance to the extent that the input equivalent noise power spectral density is halved or, equivalently, the output signal to noise ratio is doubled. Throughout the specification such a receiver is denoted a "dual sensing opto-electronic receiver" or "dual sensing receiver" for brevity. In the dual sensing receiver of Figure 2 a second augmented amplifier 14 similar to the augmented amplifier 12 of Figure 1(c) is employed for sensing the photodetector signal current, $-i_s(t)$, at a second terminal of the photodetector 10.

The result that a dual sensing receiver can have a signal to noise ratio which is double that of a standard receiver will now be demonstrated using a standard model for a typical photodetector, such as a silicon p-i-n photodiode. Figure 3(a) shows the standard opto-electronic receiver of Figure 1(c) in which the photodetector 10 is modelled by an ideal current source 16 in parallel with a capacitor C_{pd}. In this model, the ideal current source consists of two components $i_s(t)$ which is the signal current in response to incident radiation, and $i_d(t)$ which accounts for the background or dark current shot noise. For the purposes of demonstrating the principle involved, consider an ideal noiseless photodiode in which $i_d(t) = 0$ and $C_{pd} = 0$. Furthermore, it is assumed the augmented amplifier 12 is such that its passband transimpedance gain is $T_s(0)$ V/A, the noise of the augmented amplifier 12 can be modelled by a current source 13, at the amplifier input which has a constant power spectral density of G_A A^2/Hz (double sided) and the noise equivalent bandwidth of the augmented amplifier is B_n Hz. The noise source signal $i_1(t)$ is filtered by the amplifier and the output noise signal denoted, $n_1(t)$, has a variance equal to $\sigma^2_A T^2_s(0)$ V^2 where $\sigma^2_A = 2G_A B_n$ A^2. It then follows, for the case where the signal current, $i_s(t)$, is passed undistorted by the amplifier, that the output signal, $v_o(t)$ is:

$$v_o(t) = T_s(0)\, i_s(t) + n_1(t) \qquad (2)$$

and, hence, the output signal to noise ratio, denoted SNR_S is:

$$SNR_S=\frac{\overline{i^2}}{\sigma_A^2} \qquad (3)$$

where $\overline{i_s^2}$ is the mean squared value of $i_s(t)$.

Figure 3(b) illustrates the same photodiode 16 in the dual sensing optical receiver of Figure 2. Again, it is assumed that $i_d(t) = 0$ and $Cpd = 0$. The first and second augmented amplifiers 12, 14 are the same as the augmented amplifier 12 in the standard receiver of Figure 3(a) in the sense of having the same passband transimpedance gain, $T_s(0)$, input equivalent noise current sources, 13 and 15, with the same power spectral density, and the same equivalent noise bandwidth. For such a structure the output signal level is the difference between the output voltages of the upper and lower amplifiers, denoted, respectively, $v_N(t)$ and $w_N(t)$, i.e.:

$$v_o(t)=v_N(t)-w_N(t) \qquad (4)$$

For the case of the signal current $i_s(t)$ being passed undistorted by the amplifiers the amplifier output voltages, $v_N(t)$ and $w_N(t)$, respectively, are given by:

$$v_N(t)=T_s(0)\,i_s(t)+n_1(t) \qquad (5)$$

$$w_N(t)=-T_s(0)\,i_s(t)+m_1(t) \qquad (6)$$

with $n_1(t)$ being the output noise signal due to $i_1(t)$ in the upper amplifier and $m_1(t)$ being the output noise signal in the lower amplifier due to $j_1(t)$. It then follows that:

$$v_o(t)=2T_s(0)i_s(t)+n_1(t)-m_1(t) \tag{7}$$

Since the noise sources $i_1(t)$ and $j_1(t)$ arise from independent physical mechanisms, and both $n_1(t)$ and $m_1(t)$ have identical variances defined by $T^2_s(0)\sigma^2_A$, the output signal to noise ratio, denoted SNR_D, is:

$$SNR_D = \frac{2\overline{i_s^2}}{\sigma_A^2} \tag{8}$$

From equation 8, it can be seen that the signal to noise ratio has been doubled by sensing the photodetector current at both terminals of the photodiode. This doubling is achieved because the photodetector signal current at the input to the upper and lower amplifiers 12, 14 is correlated whilst the noise currents are uncorrelated. The doubling of the signal to noise ratio in a dual sensing receiver is consistent with the input equivalent noise power spectral density of the receiver being halved. Note also that the low frequency transimpedance of the dual sensing receiver is $2T_s(0)$ and, hence, twice that of a standard receiver.

Next, consider the effect on the ideal performance noted above for a dual sensing receiver by the photodetector dark current, $i_d(t)$. In the standard receiver shown in Figure 3(a) the photodetector capacitance, *Cpd*, is assumed to be zero and the photodetector dark current, $i_d(t)$, is assumed to have a power spectral density of G_d A^2/Hz (double sided). The output noise signal due to $i_d(t)$ is denoted as $n_d(t)$. It then follows that the variance of $n_d(t)$ is $\sigma^2_D T_S(0)$ where $\sigma^2_D = 2G_d B_n A^2$. The output signal of the standard receiver then is:

$$v_o(t)=T_s(0)i_s(t)+n_d(t)+n_1(t) \tag{9}$$

where, as previously defined, $n_1(t)$ is the output noise signal due to the input equivalent noise source, $i_1(t)$, of the amplifier. It then follows that the output signal to noise ratio is:

$$SNR_S = \frac{\overline{i_s^2}}{\sigma_D^2 + \sigma_A^2} = \frac{\overline{i_s^2}}{\sigma_A^2} \cdot \frac{1}{1 + \sigma_D^2/\sigma_A^2} \tag{10}$$

When the same photodiode model is used in the dual sensing receiver of Figure 3(b) the output signal level is given by:

$$v_o(t) = v_N(t) - w_N(t) \tag{11}$$

where $v_N(t)$ and $w_N(t)$, respectively are:

$$v_N(t) = T_s(0)\, i_s(t) + n_1(t) + n_d(t) \tag{12}$$

$$w_N(t) = -T_s(0)\, i_s(t) + m_1(t) - n_d(t) \tag{13}$$

Hence:

$$v_o(t) = 2T_s(0)\, i_s(t) + 2n_d(t) + n_1(t) - m_1(t) \tag{14}$$

and the output to noise ratio is:

$$SNR_D = \frac{\overline{i_s^2}}{\sigma_D^2 + \sigma_A^2/2} = \frac{2\overline{i_s^2}}{\sigma_A^2} \cdot \frac{1}{1 + 2\sigma_D^2/\sigma_A^2} \tag{15}$$

The ratio of the signal to noise ratio of the dual sensing to the standard receiver then is:

$$\frac{SNR_D}{SNR_S} = 2 \cdot \frac{1 + \sigma_D^2/\sigma_A^2}{1 + 2\sigma_D^2/\sigma_A^2} \tag{16}$$

This ratio is plotted in Figure 4 as a function of σ^2_D/σ^2_A. This Figure shows, consistent with the results of the ideal case discussed above, where $i_d(t) = 0$, that as the photodetector noise becomes negligible, i.e. as $\sigma^2_D/\sigma^2_A \to 0$, the signal to noise ratio of a dual sensing receiver approaches a value which is double that of a standard receiver. For the case where the photodetector noise is equal to 10% of the amplifier noise, i.e. $\sigma^2_D/\sigma^2_A = 0.1$ the signal to noise ratio of the dual sensing receiver is close to 80% higher than that of a standard receiver. This value drops to 33% when the photodetector noise equals the amplifier noise.

From a comparison of equations 10 and 15 above, it is clear given the assumptions made, that the dual sensing receiver halves the effect of the amplifier noise, or alternatively, halves the amplifier contribution to the input equivalent noise power spectral density. In contrast, the effect of the photodiode dark current noise is the same in the dual sensing and standard receivers. The rationale for the dual sensing receiver is that the amplifier contribution to the input equivalent noise can be halved. This is of clear interest when the receiver input equivalent noise is dominated by the amplifier and not the photodetector noise. This is typically the case when non-avalanche photodiodes are used, e.g. p-i-n or MSM (metal-semiconductor-metal) photodiodes.

To consider the effect of the photodiode capacitance on the performance of a dual sensing receiver the full photodiode model 16 of Figure 3a needs to be used. Unlike the previous two cases, when the photodiode capacitance is included in the photodiode model, the analysis of the noise performance of the dual sensing receiver is complex as the photodiode capacitance couples the effect of any given noise source in the upper augmented amplifier 12 in Figure 3b to the lower augmented amplifier 14, and vice versa. Analysis has shown that, in general, the amplifier contribution to the total noise in a dual sensing receiver will approach a value of half that of the corresponding level in a standard receiver when the following two conditions hold: first, the magnitude of the impedance of the photodiode capacitance is greater than the magnitude of the augmented amplifier input impedance for all frequencies of interest. Second, the dominant source(s) of noise occur at node(s) whose transimpedance transfer functions to the amplifier output are relatively unaffected by the photodiode capacitance. For the specific case where the dominant noise source in the augmented amplifier occurs at the amplifier input the amplifier contribution to the total noise in a dual sensing receiver will approach a value of half that of the corresponding level in a standard receiver. This case is approximated in practical transimpedance amplifiers, for example, when the amplifier noise is dominated by the noise of the feedback resistor.

Analysis has shown that the bandwidth of the dual sensing receiver, as implemented according to Figure 3(b), approaches that of the standard receiver when the magnitude of the impedance of the photodiode capacitance is greater than the magnitude of the augmented amplifier input impedance for all frequencies of interest. This is often the case.

To demonstrate that a practical dual sensing receiver incorporating a standard photodiode can exhibit a noise level approaching half that of a standard receiver, or, equivalently, a signal to noise ratio that is double that of a standard receiver the transimpedance amplifier 24 in Figure 5 was used as the basis for both a standard and a dual sensing receiver. Both receivers were driven by a standard Si p-i-n photodiode with a dark current of 25pA and a capacitance of 1.5pF at the chosen bias conditions. The transimpedance amplifier is based on a low noise 2N4416 JFET 22 in a common source configuration. The input capacitance of this stage is of the order of 10pF and is significantly higher than that of the photodiode. The feedback resistor is 100MΩ and its noise is much greater than the noise of the photodiode dark current which is of the order of 25 pA. The midband transimpedance gain of this receiver is 10^8. The 20 KΩ resistor and 1 nF capacitor in the feedback path compensate for the parasitic capacitance, of the order of 0.2 pF, across the feedback resistor. With correct compensation the experimentally measured receiver bandwidth is 20 KHz. Other parameters for this amplifier are tabulated in Table 1.

TABLE 1 - Parameters for JFET Amplifier

Parameter	Value
g_m	0.0045 mho
C_{gs}	4.0 pF
C_{gd}	0.8 pF
C_{pd}	1.5 pF
I_g	5 pA
I_d	6 mA
V_{gs}	0 V
V_{ds}	4.5 V
Drain Resistance, R_d	1500
Op. Amp. Input Impedance	» R_d
Op. Amp. Output Impedance	≈ 0 Ω

Analysis of the small signal equivalent model of the standard receiver of Figure 5 shows that, for frequencies of interest, the input equivalent noise is dominated by the feedback resistor noise and the PIN photodiode dark current noise according to:

$$G_{eqS}(f) = qI_d + \frac{2KT}{R_f} \qquad A^2/Hz \tag{17}$$

where K is Boltzmann's constant ($1.38x10^{-23}$ J/K), T is the absolute temperature, q is the electronic charge ($1.6x10^{-19}$ C), I_d is the photodiode dark current and R_f is the feedback resistor. When the dark current shot noise is small in comparison with the feedback resistor noise the input equivalent noise is:

$$G_{eqS}(f) = \frac{2KT}{R_f} \qquad A^2/Hz \tag{18}$$

Similarly, analysis of the dual-sensing receiver of Figure 6 shows, for frequencies of interest, that the input equivalent noise power spectral density is:

$$G_{eqD}(f) = qI_d + \frac{KT}{R_f} \approx \frac{KT}{R_f} \qquad A^2/Hz \tag{19}$$

and at a level which is close to half that of the standard receiver shown in Figure 5. The experimentally measured transimpedance bandwidth for the dual sensing receiver, at 18.5 KHz, is slightly lower than that of the standard receiver (20 KHz).

Experimental results confirming the halving of the amplifier input equivalent noise power spectral density are shown in Figure 7 where normalised plots of the output power spectral density for both the dual sensing and standard receives are displayed. The normalisation is with respect to the low frequency transimpedance gains, respectively, $2x10^8$ and 10^8. In the frequency range up to 10 KHz where the transimpedance transfer function is constant these plots represent the input equivalent noise power spectral density. The mean levels, obtained by averaging the values from 700 points between 200 and 1600 Hz, for the dual sensing and standard receivers, respectively, are: $4.5x10^{-29}A^2/Hz$ and $8.6x10^{-29}A^2/Hz$. The ratios of these input equivalent power spectral densities is 1.9 and, hence, in a fixed bandwidth the expected ratio of signal to noise ratios, SNR_D/SNR_S, is 1.9.

Since, $G_{eqS}(f) = qI_d+2kT/R_f = 8.6x10^{-29}$, $G_{eqD}(f) = qI_d+kT/R_f = 4.5x10^{-29}$ and $kT/R_f = 4.1x10^{-29}$ the photodiode dark current power spectral density is $0.4x10^{-29}A^2/Hz$ which is consistent with a photodiode dark current of 25 pA. Thus, given a fixed bandwidth, the ratio of the detector dark current noise variance to the input equivalent amplifier noise variance (standard receiver) equals 0.05 and, hence, from Figure 4 the expected ratio SNR_D/SNR_S is 1.9 which correlates with the value noted above.

Finally, the rise in the input equivalent noise power spectral densities at frequencies close to 10 Hz is attributed to the flicker noise of the photodetector. The low flicker noise corner frequency of the order of 10 Hz ensures that the rms contribution of flicker noise to the total rms noise of the receiver is negligible.

To ascertain the performance of a dual sensing receiver based on existing high speed (multi Gbit/sec) amplifiers a HEMT and a HBT receiver that have been presented in the literature were analysed. The following conclusions were drawn: first as the dominant noise source in a HBT amplifier occurs at the amplifier input such devices are ideal for implementing dual sensing receivers. Second, as the dominant noise source in a HEMT is at the HEMT output, and the transimpedance from this node to the amplifier output can be sensitive to the photodiode capacitance, such devices are not as suitable for implementing dual sensing receivers as are HBT based amplifiers. As to be expected, the parameters of the device being used dictate whether that device can be used to implement a dual sensing receiver with a lower level of noise than a standard receiver.

It is possible to trade the improved noise performance of a dual sensing receiver for better overload performance. That is, for the same noise level a dual sensing receiver can exhibit better overload performance than its standard counterpart.

Figure 8 illustrates an alternative dual sensing structure for transimpedance amplifiers. In the dual sensing receiver of Figure 8 a photodetector 30 has first and second transimpedance amplifiers 32, 34 connected to its first and second terminals respectively similar to the dual sensing receiver of Figure 2. However, in this embodiment the feedback signal for the transimpedance amplifiers is derived from the output stage of the receiver after the amplifier output voltages have been subtracted from each other. Preliminary analysis indicates that this structure has a greater bandwidth than that of a standard receiver.

The above theory is also applicable to a class of opto-electronic receivers that use two port networks, between the photodetector and the first active stage, to reduce the input equivalent noise. By considering the two port network and subsequent amplifier as a single entity with an equivalent model as shown in Figure 1(c), the above analysis and results are applicable.

From the theory presented and the preferred embodiments described above, it will be apparent to persons skilled in the electronic arts that numerous variations and modifications may be made to the described embodiments, in addition to those already described, without departing from the basic inventive concepts. All such variations and modifications are to be considered within the scope of the present invention, the nature of which is to be determined from the foregoing description.

CLAIMS

1. A dual sensing opto-electronic receiver comprising:

a photodetector for generating an electrical signal in response to incident radiation and having first and second terminals;

an amplifying means connected to both said first and second terminals for sensing said electrical signal whereby, in use, the input equivalent noise of the receiver is substantially reduced.

2. A dual sensing opto-electronic receiver as defined in claim 1, wherein said amplifying means comprises a first amplifier connected to said first terminal for sensing said electrical signal and producing a first output signal; and,

a second amplifier connected to said second terminal for sensing said electrical signal and producing a second output signal.

3. A dual sensing opto-electronic receiver as defined in claim 2, further comprising combining means operatively connected to said first and second amplifiers for combining said first and second output signals.

4. A dual sensing opto-electronic receiver as defined in claim 3, wherein said first and second output signals are subtracted from each other in said combining means.

5. A dual sensing opto-electronic receiver as defined in claim 4, wherein said photodetector is a photodiode.

6. A dual sensing opto-electronic receiver as defined in claim 5, wherein the magnitude of the photodiode impedance is large in comparison with the magnitude of the input impedance of the following amplifiers, the photodetector noise is less than the input equivalent noise of the following amplifiers, and the dominant amplifier noise source occurs at the amplifier

input.

7. A dual sensing opto-electronic receiver as defined in claim 6, wherein said first and second amplifiers are substantially identical transimpedance amplifiers.

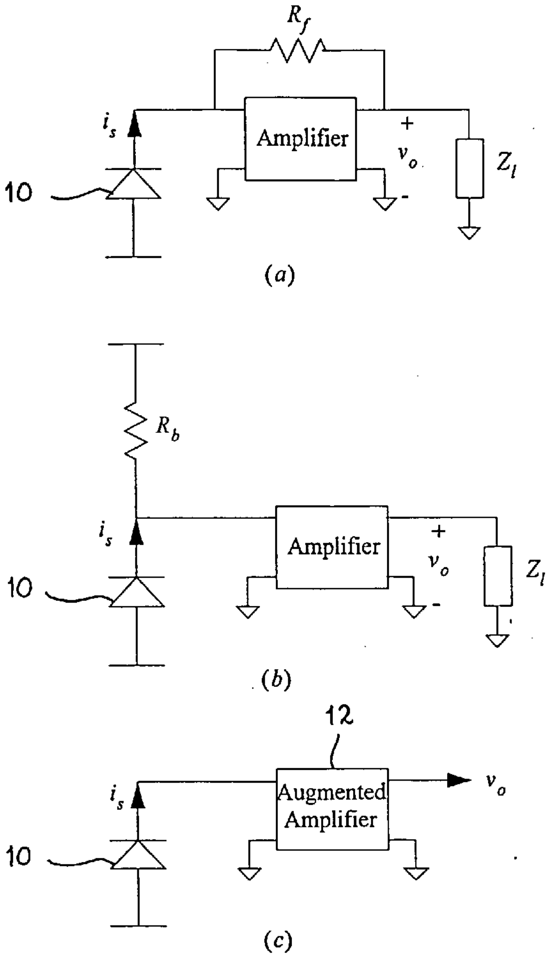
8. A dual sensing opto-electronic receiver as defined in claim 7, wherein each said transimpedance amplifier is based on a low noise JFET in common source configuration.

9. A dual sensing opto-electronic receiver as defined in claim 7, wherein a feedback signal for the transimpedance amplifiers is derived from an output stage of the receiver after the amplifier output voltages have been subtracted from each other.

10. A dual sensing opto-electronic receiver substantially as herein described with reference to and as illustrated in one or more of Figures 2, 3(b), 6 and 8, in the accompanying drawings.

Dated this 18th day of March 1999
CURTIN UNIVERSITY OF TECHNOLOGY
By Its Patent Attorneys

GRIFFITH HACK
Fellows Institute of Patent
Attorneys of Australia.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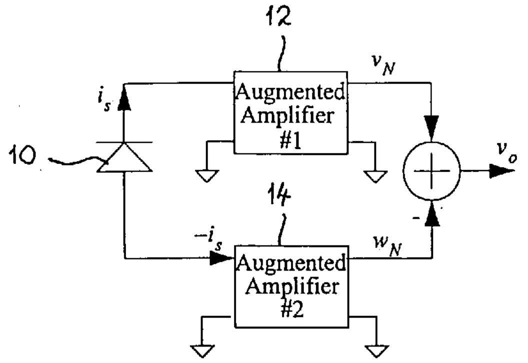
i_s
Amplifier
+
v_o
-
Z_l
10
(a)
R_b
i_s
Amplifier
+
v_o
-
Z_l
10
(b)
12
i_s
Augmented Amplifier
v_o
10
(c)

FIG. 1.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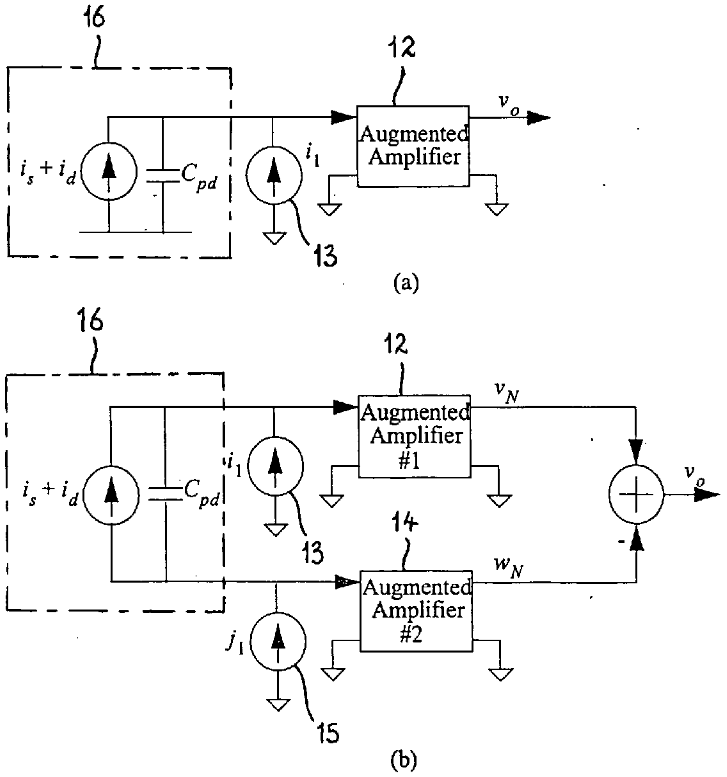
v_N
i_s
10
v_o
-
14
$-i_s$
w_N
Augmented Amplifier #2

FIG. 2.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12
v_o
Augmented Amplifier
$i_s + i_d$
C_{pd}
i_1
13
16
12
v_N
Augmented Amplifier #1
v_o
$i_s + i_d$
C_{pd}
i_1
13
14
w_N
-
Augmented Amplifier #2
j_1
15

(a)

(b)

FIG. 3.

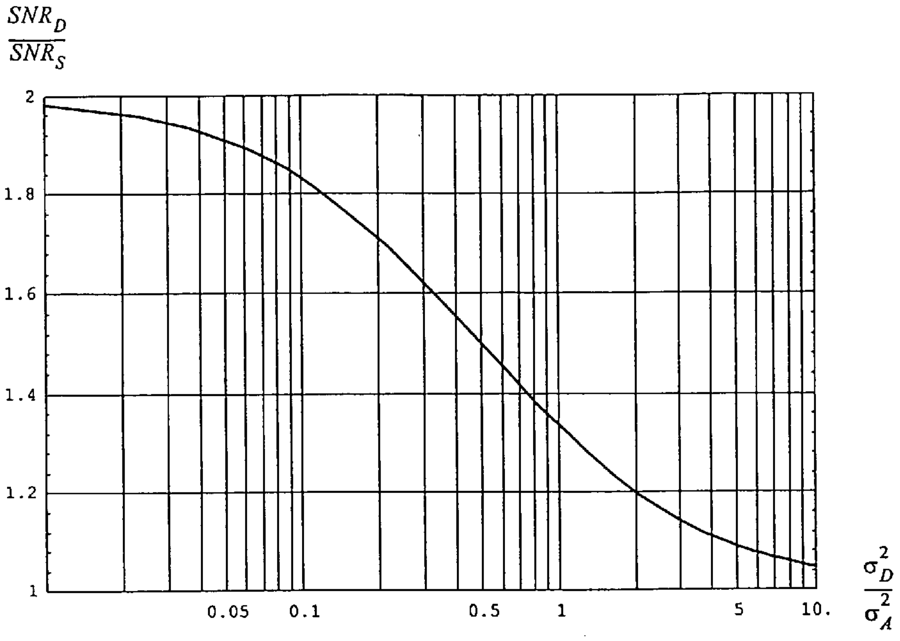
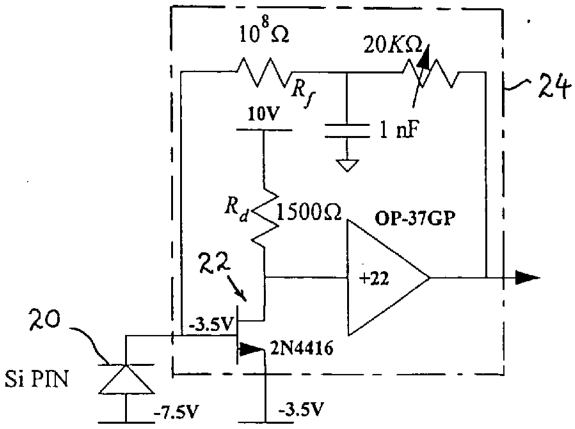

$\frac{SNR_D}{SNR_S}$
2
1.8
1.6
1.4
1.2
1
0.05
0.1
0.5
1
5
10.
$\frac{\sigma_D^2}{\sigma_A^2}$

FIG. 4.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R_f
$20K\Omega$
24
10V
1 nF
R_d
1500Ω
OP-37GP
+22
22
20
-3.5V
2N4416
Si PIN
-7.5V
-3.5V

FIG. 5.

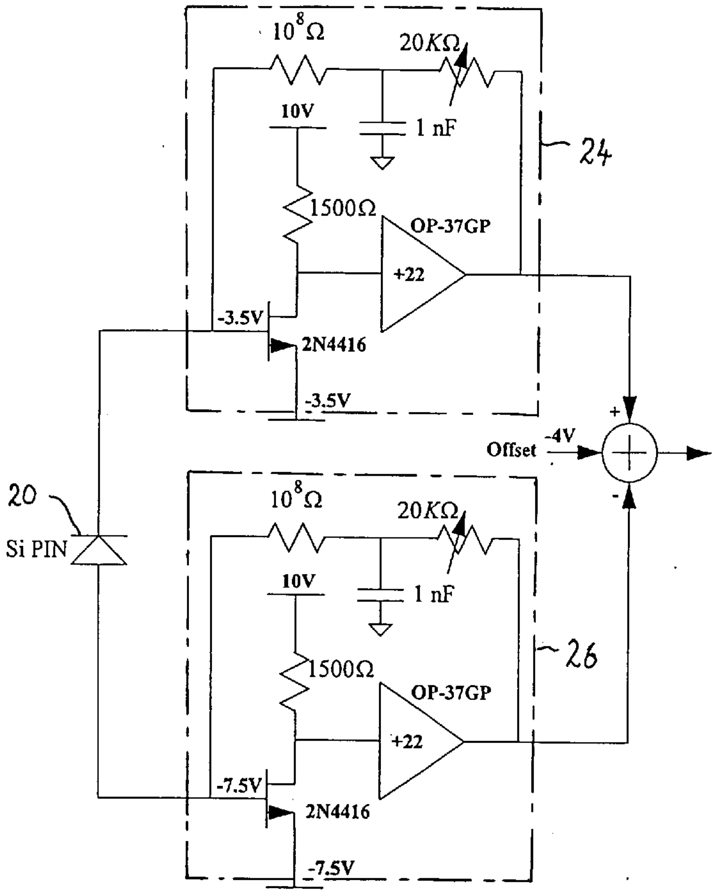
10⁸Ω
20KΩ
10V
1 nF
24
1500Ω
OP-37GP
+22
-3.5V
2N4416
-3.5V
+
Offset
-4V
-
20
Si PIN
10⁸Ω
20KΩ
10V
1 nF
26
1500Ω
OP-37GP
+22
-7.5V
2N4416
-7.5V

FIG. 6.

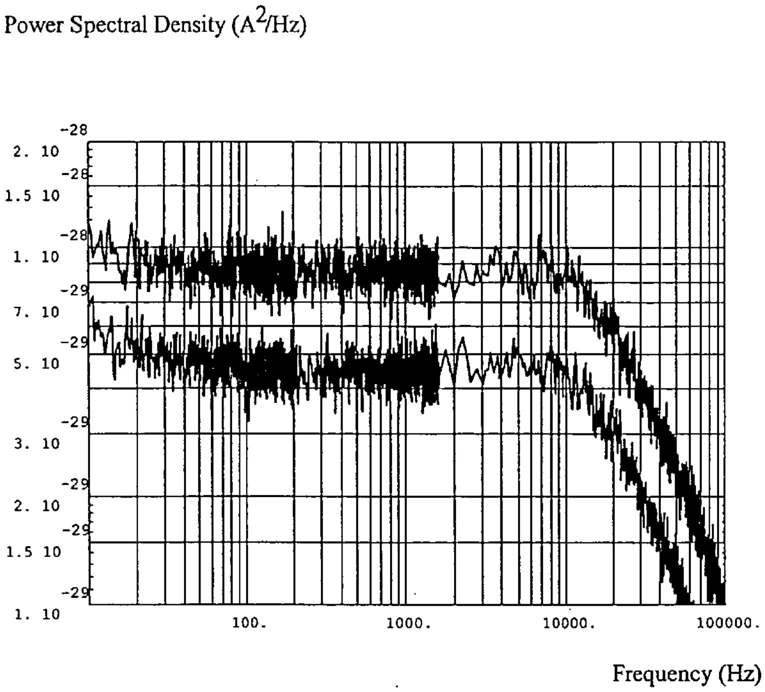
Power Spectral Density (A^2/Hz)
2. 10^-28
1.5 10^-28
1. 10^-28
7. 10^-29
5. 10^-29
3. 10^-29
2. 10^-29
1.5 10^-29
1. 10^-29
100.
1000.
10000.
100000.
Frequency (Hz)

FIG. 7.

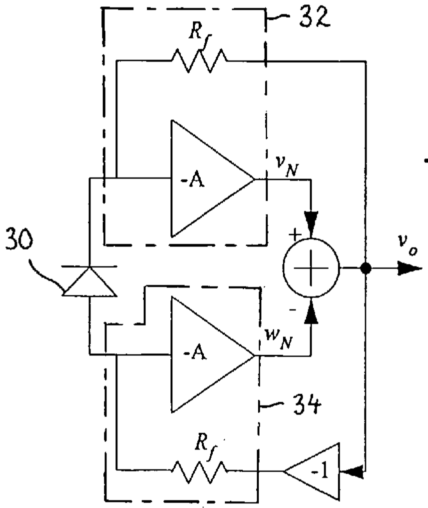
32
R_f
-A
v_N
+
v_o
30
-
-A
w_N
34
R_f
-1

FIG. 8.