

Serial Number 09/684,080
Filing Date 10 October 2000
Inventor Vinson L. Go

NOTICE

The above identified patent application is available for licensing. Requests for information should be addressed to:

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
CODE 00CC
ARLINGTON VA 22217-5660

20010713 024

2
3 LOW-NOISE WIDEBAND HETERODYNE OPTICAL ARRAY RECEIVER

4
5
6 STATEMENT OF THE GOVERNMENT INTEREST

7 The invention described herein may be manufactured and used
8 by or for the Government of the United States of America for
9 Governmental purposes without the payment of any royalties
10 thereon or therefore.

11
12 BACKGROUND OF THE INVENTION

13 (1) Field of the Invention

14 The present invention relates generally to detection of
15 optical signals and, more specifically, to apparatus and methods
16 for low-noise and wide bandwidth detection of light signals from
17 an optical array.

18 (2) Description of the Prior Art

19 Fiber optic sensor systems, such as fiber optic passive
20 acoustic sensor systems, may typically produce and utilize
21 infrared coherent light wave that is modulated by an acoustic
22 field for detection at a photoreceiver. The received light
23 signal must be converted into electrical signals by a receiver

1 circuit whereupon the electrical signals can then be further
2 processed by other electronics.

3 A typical optical detection system for receiving light from
4 a fiber optic system utilizes a single photodetector followed by
5 an amplifier. The amplifier is usually an operational amplifier
6 configured in a high gain transimpedance circuit for converting
7 an electrical current signal into an electrical voltage signal.
8 The necessary high gain makes it difficult to design a stable
9 operational amplifier circuit. Moreover, the prior art optical
10 detection systems have a bandwidth of a few megahertz due to the
11 limited frequency response of the operational amplifier and or
12 the photodiode. As well, prior art optical detection systems are
13 responsive to light intensity noise thereby limiting sensitivity.
14 Prior art patents that relate to this topic include the
15 following:

16 U. S. Patent No. 4,862,896 issued Sep. 19, 1989 to Joachim
17 Pietzsch, discloses that superheterodyne receivers for optical
18 signals can be composed of two branches. The first branch
19 contains a superheterodyne receiver in which the reception signal
20 and the signal of a local oscillator are mixed in a traditional
21 way; in the second receiver branch, the signal of the local
22 oscillator experiences a 90 degree phase rotation before the mixing.
23 An optical triple coupler inventively serves for dividing the

1 reception light and the light of the local laser onto both
2 reception branches. This triple coupler can be manufactured as a
3 triple fiber coupler or, on the other hand, has an integrated-
4 optical triple coupler of lithium niobate, glass or of a III-V
5 semiconductor.

6 U. S. Patent No. 5,422,752 issued Jun. 6, 1995 to Ian
7 Hardcastle, discloses an optical transmission system utilizing at
8 a transmitter continuous phase frequency shift keyed modulation
9 of a laser and a coherent heterodyne receiver therefor, the
10 system including at the transmitter means for imposing a low
11 frequency modulation on the transmitter optical power and
12 frequency deviation and at the receiver means for extracting
13 from the receiver AGC control signal a replica of the low
14 frequency modulation, means for demodulating the modulated
15 frequency deviation of the received optical signal synchronously
16 with respect to the extracted low frequency signal, means for
17 deriving from the de-modulated signal an error signal and a
18 control system responsive to the error signal to control the
19 receiver local oscillator frequency.

20 U. S. Patent No. 5,463,461 issued Oct. 31, 1995 to Horiuchi
21 and Ryu, discloses that a coherent optical receiver is
22 characterized in that it comprises a local oscillator light,
23 source, for amplifying a local oscillator light, a light

1 combining/dividing unit, a dual balanced receiver which comprises
2 two optical detectors, and an electrical amplifier. Therefore,
3 the coherent optical receiver has the characteristic that the
4 length of the non-repeating section of an optical communication
5 system including the device and employing heterodyne detection
6 can be increased, or the dynamic range of an optical measuring
7 system including this receiver and employing heterodyne detection
8 can be widened.

9 U. S. Patent No. 5,477,369 issued Dec. 19, 1995 to Mahon and
10 Khoe, describes a device for optical heterodyne detection, using
11 only two adjustable elements influencing the state of
12 polarization and having a limited control range (51, 52) in order
13 to realize an endless polarization control. In a first
14 embodiment a temporary loss of signal intensity of at most 3 dB
15 is accepted. This signal loss is avoided if a circuit of non-
16 adjustable optical components (81, 82, 83) is incorporated in the
17 heterodyne detection device.

18 U. S. Patent No. 5,510,927 issued Apr. 23, 1996 to Reinhold Noe,
19 discloses novel structure and methods for tuning the local
20 oscillator of an optical superheterodyne receiver. In a first
21 method, the value of the local oscillator frequency at which the
22 maximum of the chronological average of the output signal from
23 the demodulator occurs is used to set the local oscillator

1 frequency. An alternate method includes first and second
2 discriminators used to receive the intermediate frequency signal.
3 The separate discriminator characteristics of the first and
4 second frequency discriminators are used in setting the local
5 oscillator frequency.

6 U. S. Patent No. 5,400,167 issued Mar. 21, 1995 to Yoshihiko
7 Suemura, discloses an automatic frequency control system, for an
8 optical coherent communication system, in which the frequency of
9 local oscillation light 5 from a coherent light communication
10 receiver 100 is swept to pull the intermediate frequency to a
11 stable AFC point. The AFC is caused to operate with an
12 intermediate frequency in the AFC operation range, and
13 interrupted. Subsequently while sweeping the frequency of local
14 oscillation light 5 in a certain direction in a predetermined
15 range, the output voltage of frequency discriminator 9 is
16 monitored. Once the change of the output voltage of frequency
17 discriminator 9 due to the sweep exceeds the predetermined
18 threshold value, the AFC resumes for pulling to a stable point.

19 U. S. Patent No. 5,757,531 issued May 26, 1998 to Tomesen et
20 al, discloses that an optical heterodyne receiver converts a
21 received modulated optical signal into an electrical IF signal by
22 an IF converter which includes a local laser, a coupling element
23 and an opto-electrical converter. The IF signal is converted into

1 a demodulated signal by a demodulator having a quadratic transfer
2 characteristic. To permit a relatively low intermediate
3 frequency, the IF converter converts the received signal into two
4 quadrature IF signals and in the demodulator two sub-demodulators
5 recover therefrom two demodulated signals which are then
6 combined. This eliminates unwanted quadratic components in the
7 combined signal.

8 In summary, while the prior art shows various optical signal
9 receivers, the above disclosed prior art does not show an optical
10 signal receiver having a bandwidth greater than one Gigahertz
11 which utilizes matched photodiodes for suppressing intensity
12 noise by means of common mode rejection. Consequently, there
13 remains a need for a system that provides improved amplifier
14 stability, wide bandwidth operation, while suppressing light
15 intensity noise. Those skilled in the art will appreciate the
16 present invention that addresses the above and other problems.

17
18 SUMMARY OF THE INVENTION

19 Accordingly, it is an object of the present invention to
20 provide an improved optical receiver.

21 It is yet another object of the present invention to use
22 matched photodiodes connected in a differencing mode to suppress
23 intensity noise.

1 It is another object of the present invention to provide a
2 stable amplifier for a detected light signal using a miniature
3 microwave integrated circuit.

4 These and other objects, features, and advantages of the
5 present invention will become apparent from the drawings, the
6 descriptions given herein, and the appended claims.

7 In accordance with the present invention, a low-noise method
8 for detecting an optical signal is disclosed. The method
9 includes steps such as providing a first photodiode and a second
10 photodiode for receiving the optical signal wherein the first
11 photodiode and the second photodiode may be selected such that a
12 first frequency response of the first photodiode is within one
13 percent of a second frequency response of the second photodiode
14 over a selected bandwidth. Preferably the photodiodes are
15 connected to operate in a differencing mode such that, for
16 instance, a cathode of the first photodiode is connected to an
17 anode of the second photodiode to form a connection point. The
18 optical signal is combined with a reference signal such as a
19 local oscillator signal or other signal to produce a combined
20 signal. The combined signal may be split into two preferably
21 equal parts to form a first combined signal and a second combined
22 signal. The first combined signal is applied to the first
23 photodiode and the second combined signal is applied to the

1 second photodiode. The resulting signal is a reduced noise
2 signal formed at the connection point.

3 In one preferred embodiment, the first photodiode and the
4 second photodiode are both formed on the same semiconductor
5 wafer. The first photodiode and second photodiode may also be
6 hand selected from a group of photodiodes. The bandwidth for the
7 selected diodes is preferably greater than at least one
8 Gigahertz. To reduce noise, the first photodiode and the second
9 photodiode should each preferably have a very low dark current.
10 Especially for hand selection, the first photodiode and the
11 second photodiode should be tested to verify the first frequency
12 response and the second frequency response. For hand selection,
13 the method further comprises manually selecting the first
14 photodiode and the second photodiode from a group of photodiodes
15 based on the first frequency response and the second frequency
16 response.

17 The step of amplifying comprises utilizing at least one low-
18 noise miniature microwave integrated circuits for amplifying the
19 reduced noise signal. However a presently preferred embodiment
20 comprises utilizing at least two low-noise miniature microwave
21 integrated circuits for amplifying the reduced noise signal.

22 A biasing network is provided for the low-noise miniature
23 microwave integrated circuits. Preferably the same biasing

1 network is used to connect two low-noise miniature microwave
2 integrated circuits together. A band-reject network is
3 preferably provided as an integral part of the biasing network.
4 The components for the band-reject network are preferably chosen
5 based on the selected bandwidth. The bias network (inductor and
6 resistor) provide a DC bias to the miniature microwave circuit
7 while preventing the RF signal from "escaping" through the input
8 bias port. It is desirable to utilize a highly filtered power
9 supply to provide one or more bias voltages for the biasing
10 network. In a preferred embodiment, a fifty ohm transmission
11 line is utilized for connecting between the connection point and
12 the amplifier.

13 In other words, a method is provided for detecting an
14 optical signal that comprises providing a first photodiode having
15 a first frequency response over a selected bandwidth of over one
16 Gigahertz and providing a second photodiode having a second
17 frequency response over the bandwidth. The first frequency
18 response and the second frequency response are preferably within
19 one percent over the bandwidth. An anode of the first photodiode
20 may be connected to a cathode of the second photodiode at a
21 connection point such that the first photodiode and second
22 photodiode operate in a differencing mode. The optical signal is
23 applied to the first photodiode and to the second photodiode and

1 the resulting signal is amplified preferably using a miniature
2 microwave integrated circuit.

3 Optical components are therefore provided for detecting an
4 optical signal. The optical components comprise a combiner for
5 combining a reference optical signal and a modulated optical
6 signal and a first photodiode and a second photodiode. The
7 cathode of the first photodiode may be connected to an anode of
8 the second photodiode at a connection point. The first
9 photodiode and the second photodiode each may be operable over a
10 bandwidth of over one Gigahertz (GHz) and a miniature microwave
11 integrated circuit may be connected to the connection point.

12 The first photodiode and the second photodiode are each
13 preferably formed on the same monolithic semiconductor element.
14 The first photodiode and the second photodiode are preferably
15 each p-i-n photodiodes. A transmission line connects between the
16 connection point and the miniature microwave integrated circuit.

17

18

BRIEF DESCRIPTION OF THE DRAWINGS

19 A more complete understanding of the invention and many of
20 the attendant advantages thereto will be readily appreciated as
21 the same becomes better understood by reference to the following
22 detailed description when considered in conjunction with the
23 accompanying figure wherein corresponding reference characters

1 indicate corresponding parts throughout the view of the figure
2 and wherein:

3 The figure is a circuit diagram of a low-noise optical
4 detector in accord with the present invention.

5
6 BRIEF DESCRIPTION OF THE PREFERRED EMBODIMENTS

7 Referring now to the drawings and, more particularly, to the
8 single figure there is shown a low-noise optical signal detector
9 circuit 10 in accord with the present invention. The present
10 invention is especially useful for amplifying signals from a
11 passive optical array, such as optical array 12. Optical array
12 12 may, for instance, comprise a fiber optic sensor system with
13 one or more arrays of fiber optic acoustic sensors. However, the
14 circuit or features thereof as discussed subsequently, could also
15 be used for reducing noise, such as laser intensity noise, and to
16 provide a very sensitive, wide bandwidth, optical signal
17 detector. In a preferred embodiment, circuit 10 is a low-noise
18 heterodyne optical receiver for a fiber optic sonar array. In
19 the preferred embodiment, the purpose of the circuit is to
20 receive modulated infrared coherent light from a fiber optic
21 passive sonar system, such as optical array 12, and convert the
22 signals carried by the light into electrical signals that can be
23 further processed by other electronics (not shown). The

1 invention may detect the heterodyne signal from a high coherence
2 light such as from an interferometer.

3 Preferably reference signal 14 is combined with the optical
4 signal from optical array 12 to produce a signal that may be
5 referred to as a combined signal. Reference signal 14 may be of
6 several types including a local oscillator signal. Reference
7 signal 14 is generally unmodulated laser light acting as a local
8 oscillator signal. Reference signal 14 could also be produced as
9 part of the optical array signal and may already be combined with
10 the optical signal. Combiner/splitter 16 divides the signal
11 preferably into two equal parts such that the same optical
12 signal, with equal optical intensity noise, is applied to both
13 photodetectors 18 and 20.

14 In a preferred embodiment, the photodetectors 18 and 20 are
15 at least 1% matched p-i-n photodiodes connected to operate in a
16 differencing mode to suppress, by common mode rejection, the
17 intensity noise of the laser. Although other laser light
18 frequencies could be used, in an embodiment of the present
19 invention the laser had a wavelength of 1319 nm. By at least 1%
20 matched it is meant that the sensitivity of the photodiodes over
21 the selected bandwidth is within 1% of each other in terms of
22 conversion between watts in light power to electrical current in
23 amps. The better the match between the photodiodes, the better

1 the pair can subtract the laser noise by common mode rejection.
2 While 1% matched is given as a nominal number, it will be
3 understood that some variation with this number could be used
4 with the understanding that improving the match will improve
5 circuit operation. In a preferred embodiment, the photodiodes
6 would be produced on the same semiconductor material element or
7 wafer 22 which will typically be a monolithic semiconductor chip
8 or element. In this way, the manufacturing would enhance
9 sensitivity matching by using the same material, same production
10 conditions, availability for laser trimming, and other means.
11 However, even without such components available, the pair of
12 photodiodes can still be sensitivity matched by obtaining a batch
13 of diodes and hand testing them. Alternatively, the manufacturer
14 can be contacted for hand matching the diodes by taking
15 measurements of a whole batch of diodes and sorting them to the
16 specifications discussed herein.

17 The structure of the p-i-n diode provides a very high-speed
18 response plus a very wide bandwidth that extends from very low
19 frequency to the GHz ranges. In a preferred embodiment, the p-i-
20 n photodiodes have a frequency response up to 2 GHz wide radio-
21 frequency bandwidth. The selected p-i-n photodiodes should also
22 be chosen to have a very low dark current, i.e., the current flow
23 when the photodiode is theoretically not conducting. A very low

1 dark current results in a lower noise contribution to the
2 receiver noise.

3 In a preferred embodiment, the anode of photodiode 18 is
4 connected to the cathode of photodiode 20 to form a junction 24.
5 The opposite ends of the photodiodes are preferably connected to
6 the plus and minus voltage supplies 34. In this difference
7 configuration, the photodiodes act to reject common mode noise at
8 the frequencies found for laser intensity noise and to pass the
9 remaining combined signal at other frequencies. The reduced
10 noise signal produced at junction 24 is applied to an amplifier
11 such as amplifier 26.

12 In a preferred embodiment, a low-noise miniature microwave
13 integrated circuit 26 (MMIC) is provided to function as a
14 transimpedance amplifier and provide signal gain. Low noise
15 amplifier 26 minimizes front-end noise. An additional gain
16 stage is preferably provided by another miniature microwave
17 integrated circuit 36 which has the effect of improving the
18 signal to noise ratio at output 38.

19 A biasing network comprised of network elements such as
20 elements 28, 30, and 32 is used to provide a bias voltage to
21 miniature microwave integrated circuit 26. Elements 28, 30, and
22 32 are preferably groups of elements generally configured as
23 shown and selected based on the bandpass selected. Thus,

1 generally one or more capacitive elements as indicated by
2 effective capacitor 32 are used to a-c couple the signal to the
3 next stage, if used. Generally, one or more inductive elements
4 as indicated by effective inductor 30 are used to provide DC bias
5 current but prevent high frequency signal feedback through
6 resistive elements such as element 28 into the bias voltage as
7 indicated at 34. Likewise biasing network of elements such as
8 elements 40, 42, and 44 are used to provide biasing voltage and
9 stabilize amplifier operation by passing the a-c signal and
10 preventing feedback through the power supplies. Again the
11 components are chosen based on the selected bandwidth of
12 operation and may include one or more resistors, capacitors, and
13 inductors effectively arranged as indicated.

14 The power supplies include highly filtered voltage
15 regulators to reduce noise in optical signal receiver circuit 10.
16 The frequency response of optical signal receiver circuit 10 is
17 limited by the frequency response of photodiodes 18 and 20,
18 amplifiers 26 and 36, as well as the biasing circuit components.
19 In the preferred embodiment of circuit 10, it has been found that
20 heterodyned optical signals are detectable below -50 dBm. The
21 passband is also flat within 1.0 dB, with a frequency response up
22 to 2 GHz. The output 38 is preferably processed by other
23 electronics (not shown). Thus, the present invention may provide

1 a very wideband optical receiver with a frequency response from
2 100 kilohertz to 2 GHz.

3 Biasing voltage 34 may be provided by a voltage reference
4 network. The biasing network, e.g., elements such as 28, 30, and
5 32 and/or 40, 42, and 44 could be comprised of active network
6 elements as well as passive network elements to further optimize
7 performance. While the preferred amplifiers are miniature
8 microwave integrated circuits such as 26 and 36, other amplifier
9 types could conceivably be used such as radio-frequency
10 transistors, or integrated amplifier modules. Other types of
11 photodiodes could be used for light wavelengths other than 1319
12 cm. As well, much higher frequency response photodiodes could be
13 used so that the frequency response could be as high as 8 GHz.

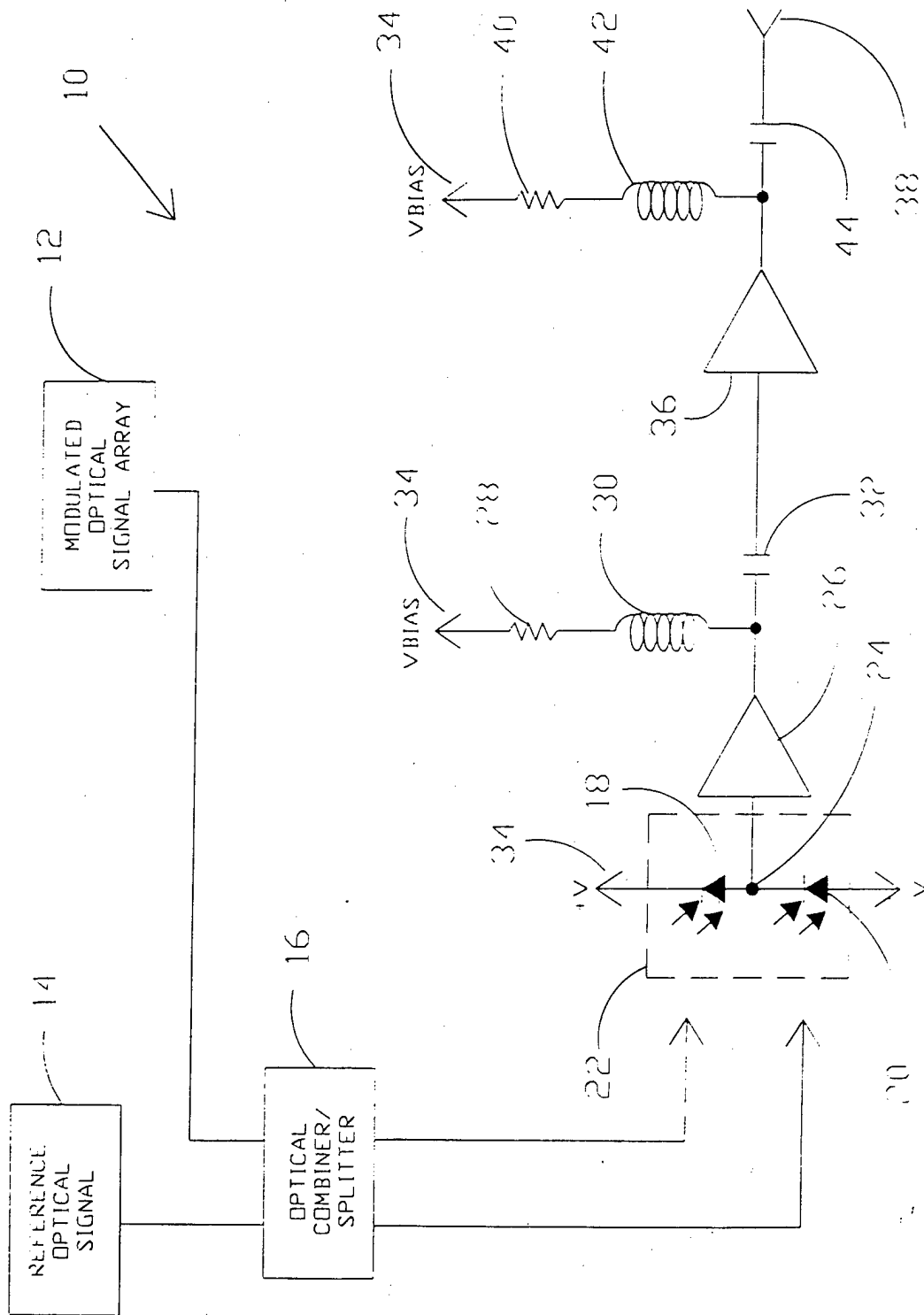
14 It will be understood that many additional changes in the
15 details, materials, steps and arrangement of parts, which have
16 been herein described and illustrated in order to explain the
17 nature of the invention, may be made by those skilled in the art
18 within the principle and scope of the invention.

19

2
3 LOW-NOISE WIDEBAND HETERODYNE OPTICAL ARRAY RECEIVER

4
5 ABSTRACT OF THE DISCLOSURE

6 A system and method is disclosed for detecting optical
7 signals that is especially suitable for use with a fiber optic
8 sonar transducer array. The system preferably uses two
9 photodiodes with a frequency response matched to within one
10 percent over a bandwidth of at least one Gigahertz to reduce
11 common mode intensity noise. Preferably the two photodiodes are
12 manufactured on the same semiconductor wafer to provide as
13 closely identical properties as possible. In one preferred
14 embodiment, two low-noise miniature microwave integrated circuits
15 are used to amplify the detected signal. A biasing network
16 biases and couples the miniature integrated circuits together.



FIGURE