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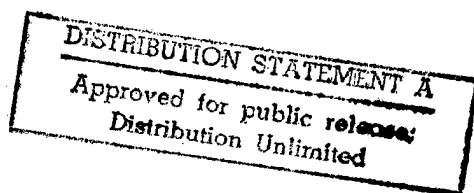
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NOTICE

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

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DTIC QUALITY INSPECTED 2

19980514 086

1 Navy Case No. 77268

2

3 SYSTEM AND METHOD FOR RECOVERING A SIGNAL OF INTEREST
4 FROM A PHASE MODULATED SIGNAL USING QUADRATURE SAMPLING

5

6 STATEMENT OF 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 CROSS REFERENCES TO RELATED PATENT APPLICATIONS

13 This instant application is related to a co-pending U.S.
14 Patent Application entitled A DEMODULATION SYSTEM AND METHOD FOR
15 RECOVERING A SIGNAL OF INTEREST FROM AN UNDERSAMPLED, MODULATED
16 CARRIER (Navy Case No. 77556) having same filing date.

17

18 BACKGROUND OF THE INVENTION

19 (1) Field Of The Invention

20 The present invention relates to systems and methods for
21 recovering signals of interest from a phase modulated signal and
22 more particularly, to a digital receiver system for receiving a

1 phase modulated signal from a fiber optic interferometer and
2 recovering a measurand signal by sampling the phase modulated
3 signal using quadrature time samples.

4 (2) Description Of The Prior Art

5 Fiber optic interferometers are highly sensitive devices for
6 the measurement of time-varying measurand fields or signals, such
7 as acoustic pressure, vibration and magnetic fields. The
8 acoustic pressure changes, vibrations or magnetic fields affect
9 the light transmitting characteristics of the optical fibers used
10 in the interferometer, producing a change in the phase of the
11 light signals traveling through the optical fibers. A
12 measurement of the change in phase of the optical signal
13 transmitted through the optical fiber is representative of the
14 changes in the environmental conditions or measurand field acting
15 on the optical fiber.

16 Typically, fiber optic interferometers utilize two optical
17 paths or fibers, and an optical source, such as a laser, which
18 provides a light signal in the optical paths. The measurand
19 signal modulates the phase of the light signal in one or both of
20 the optical paths, and the light signal thereby acts as a carrier
21 for the measurand signal. The phase modulated optical signal is
22 produced by interfering the optical signals in both paths, and

1 the components of the phase modulated signal include both the
2 carrier signal and the measurand signal.

3 One type of interferometric sensor system employs a phase
4 generated carrier concept using two quadrature carriers, for
5 example, having the frequencies ω_c and $2\omega_c$ or $2\omega_c$ and $3\omega_c$. The
6 carriers can be generated by directly modulating the optical
7 source in the interferometer at the carrier frequency ω_c or with
8 an external phase modulator that provides the carrier frequency
9 ω_c after the light signal has been generated. When the optical
10 signal having the carrier frequency of ω_c passes through the
11 interferometer sensors and is modulated by the measurand, the
12 resulting phase modulated signal includes quadrature carriers at
13 harmonics or multiples of the carrier frequency (e.g., ω_c , $2\omega_c$,
14 $3\omega_c$, $4\omega_c$, ...). Using the quadrature carriers in the demodulation
15 process prevents fading of the interferometric signal and
16 normalizes the detected signal.

17 Various demodulation techniques have been used to recover
18 the signal of interest or measurand signal from the phase
19 modulated optical signal output from a fiber optic interferometer
20 or other systems utilizing quadrature carriers. According to one
21 technique, receiver systems convert the phase modulated signal

1 from analog to digital and then use a homodyne technique to
2 demodulate and recover the measurand signals from the quadrature
3 carriers. To reconstruct the phase modulated signal, previous
4 systems used sampling rates that satisfy Nyquist's criteria,
5 i.e., a minimum sampling rate of twice the carrier frequency ω_c .
6 If the system uses quadrature carriers at ω_c and $2\omega_c$, the minimum
7 sampling rate according to the previous systems must be $4\omega_c$. The
8 high sampling rates required by these systems (i.e., at least
9 four times the lowest carrier frequency) places great demands on
10 the sampling circuitry and limits the sensor bandwidth and the
11 number of channels.

12 The use of analog circuitry, such as analog multipliers,
13 filters, integrators and differentiators, in conventional
14 receiver systems to demultiplex and demodulate signals from an
15 array of interferometers also has a number of limitations and
16 disadvantages. The components forming the analog circuits must
17 be gain and phase matched with the carrier signal during the
18 demodulation process to optimize performance, which is costly and
19 difficult to achieve. Using the conventional homodyne technique,
20 for example, to recover the measurand signal requires
21 multiplication of the quadrature carriers by a local oscillator

1 of the proper frequency, phase and amplitude. Failure to
2 adequately match the amplitude and phase results in harmonic
3 distortion, which reduces the useful dynamic range of the
4 interferometer. The output level of prior art demodulators using
5 analog circuitry is also limited by the power supply.
6 Furthermore, noisy analog circuitry (e.g., multipliers and
7 filters) can increase the noise floor of the system.

8 Fiber optic interferometer systems also commonly use an
9 array of sensors to detect the measurand field over a larger
10 area. One application for an array of fiber optic interferometer
11 sensors is to detect acoustic waves, for example, in an
12 underwater environment. If an array of fiber optic
13 interferometer sensors are used, multiple signals are multiplexed
14 on one or more fibers, for example, by using time division
15 multiplexing (TDM) or wavelength division multiplexing (WDM)
16 techniques. The phase modulated signal output from the array of
17 fiber optic interferometer sensors must be demultiplexed to
18 obtain the multiple signals of interest. One example of a TDM
19 sensor system is sampled with a pulsed optical interrogation
20 signal.

SUMMARY OF THE INVENTION

One object of the present invention is to recover a signal of interest or measurand signal from a phase modulated signal by sampling the phase modulated signal with quadrature time samples to allow higher channel count systems with higher bandwidth sensors.

Another object of the present invention is to sample and demodulate the signal using digital signal processing techniques to provide a higher dynamic range, lower electronic noise, easier operation, and repeatable performance from channel to channel.

A further object of the present invention is a digital receiver system for quadrature sampling and demodulating a phase modulated signal in any system utilizing quadrature carriers.

The present invention features a system and method of recovering one or more signals of interest from a phase modulated signal generated by a system utilizing quadrature carriers. The signals of interest are sensed by one or more sensors and modulate a carrier signal to form the phase modulated signal $f(t)$. The method comprises the steps of: receiving the phase modulated signal $f(t)$; sampling the phase modulated signal $f(t)$ using quadrature time samples of m/f_c and $m/f_c + \Delta t$, where $m \geq 1$, $f_c/m \geq 2\Delta f_h$, and Δf_h is the bandwidth of the sensors, to produce odd

1 sampled signal components and even sampled signal components; and
2 determining the signal of interest from the odd and even sampled
3 signal components.

4 The preferred method further includes the steps of: matching
5 gains of the odd sampled signal component and even sampled signal
6 component; normalizing the odd sampled signal component and the
7 even sampled signal component to form normalized odd and even
8 sampled signal components; and processing the normalized odd and
9 even sampled signal components using a differentiate and cross
10 multiply process. One example of the step of normalizing
11 includes taking the square root of the sum of the squares of the
12 odd sampled signal component and the even sampled signal
13 component and dividing.

14 The present invention also features a digital receiver
15 system comprising a quadrature sampling demodulator that samples
16 the phase modulated signal using quadrature time samples. The
17 system preferably includes a gain adjuster, responsive to the
18 quadrature sampling demodulator, for adjusting and matching gains
19 of the odd and even sampled signal components from the quadrature
20 sampling demodulator. The system can also include circuitry for
21 normalizing the odd and even sampled signal components and for
22 performing an arctangent, a differentiate and cross-multiply
23 process, or any other phase demodulation technique to recover the
24 signal of interest.

1 In one example, the system utilizing quadrature carriers is
2 a fiber optic interferometer, the sensor is a fiber optic
3 interferometer sensor, and the signal of interest is a measurand
4 signal acting on the fiber optic interferometer sensor. An
5 optical source generates an optical carrier signal that is
6 modulated by the measurand signal acting on the sensor. The
7 method further includes the step of photodetecting the phase
8 modulated signal $f(t)$ output from the fiber optic interferometer
9 sensor prior to sampling said phase modulated signal $f(t)$. In the
10 exemplary embodiment, phase modulated signal $f(t)$ preferably has
11 the form

12 $f(t) = A + B \cos(C \cos(\omega_c(t) + \phi_c) + D \cos(\omega_h(t) + \phi_h) + \Phi(t))$ where:

13 A = the DC level of light from the optical source;

14 B = the magnitude of the phase modulated signal;

15 C = the magnitude of the carrier signal;

16 ϕ_c = the phase of the carrier signal;

17 D = the magnitude of a spectrum level of the sensor;

18 ϕ_h = the phase of the signal of interest; and

19 $\Phi(t)$ = the time varying phase shift due to environmental
20 effects.

1 BRIEF DESCRIPTION OF THE DRAWINGS

2 These and other features and advantages of the present
3 invention will be better understood in view of the following
4 description of the invention taken together with the drawings
5 herein:

6 FIG. 1 is a schematic block diagram of an interferometer
7 system including a digital receiver system, according to the
8 present invention;

9 FIG. 2 is a graphical representation of the frequency
10 spectrum of a phase modulated signal, according to the present
11 invention;

12 FIG. 3 is an exploded view of the graphical representation
13 in FIG. 2 showing the sidebands around the carrier frequency f_c
14 and first multiple of the carrier frequency $2f_c$;

15 FIG. 4 is a graphical representation of the basebanded
16 sidebands for the carrier frequency f_c ;

17 FIG. 5 is a graphical representation of the basebanded
18 sidebands for the first multiple of the carrier frequency $2f_c$;
19 and

20 FIG. 6 is a schematic block diagram of the digital receiver
21 system used in the interferometer sensor system, according to one
22 embodiment of the present invention.

1 DESCRIPTION OF THE PREFERRED EMBODIMENT

2 A digital receiver system 10, FIG. 1, according to the
3 present invention, is used to recover a signal of interest from a
4 phase modulated signal in a phase generated carrier system
5 utilizing quadrature carriers. According to the exemplary
6 embodiment of the present invention, the digital receiver system
7 10 is used in a conventional fiber optic interferometer sensor
8 system 12 using a phase generated carrier concept. The present
9 invention contemplates, however, using the digital receiver
10 system 10 and the demodulation concepts of the present invention
11 with any system utilizing quadrature carriers, for example, in
12 transmission lines and/or through the radio frequency airways.

13 The exemplary interferometer sensor system 12 includes an
14 optical source 14, such as a laser, that generates an optical
15 signal in an optical path or fiber 16. According to one example,
16 an oscillator 18 directly modulates the optical source 14 to
17 produce an optical carrier signal having a frequency of ω_c .
18 Alternatively, an external phase modulator 19 can be used to
19 modulate the optical signal generated by the optical source 14 as
20 the optical signal passes through the external phase modulator
21 19. For example, the optical fiber 16 can be stretched and

1 relaxed at the carrier frequency ω_c as the optical signal passes
2 through, e.g., using a piezoelectric material bonded to the
3 fiber, thereby generating an optical signal having a frequency of
4 ω_c .

5 The optical carrier signal is transmitted through the
6 optical fiber 16 to at least one interferometer sensor 20 in
7 which the optical carrier signal is split into two optical paths
8 22, 24. At least one signal of interest 26 from a measurand
9 field, such as an acoustic pressure or a magnetic field,
10 modulates the phase of the optical carrier signal in one or both
11 of the optical paths 22, 24. The sensor 20 then produces a phase
12 modulated optical signal by interfering the optical carrier
13 signal in both of the optical paths 22, 24. The phase modulated
14 optical signal has an interference pattern corresponding to the
15 sensed change in the measurand field or signal of interest 26.

16 In one embodiment, the system 12 includes an array of
17 interferometer sensors 20 connected in series. The measurand
18 signals 26 sensed by each of the sensors 20 are multiplexed on a
19 single output optical fiber 28 using either time division
20 multiplexing (TDM) or wavelength division multiplexing (WDM), or

1 a combination of both. TDM sensor systems are sampled with a
2 pulsed optical interrogation signal.

3 The phase modulated optical signal is then detected with a
4 photodetector 30 to convert the phase modulated optical signal
5 into a phase modulated electrical signal $f(t)$ that varies with
6 time. The phase modulated electrical signal $f(t)$ detected from
7 the interferometer sensors 20 has the following form:

$$\begin{aligned} f(t) &= A + B \cos(C \cos(\omega_c t + \phi_c) + \theta(t)) \\ &= A + B \cos(C \cos(\omega_c t + \phi_c) + D \cos(\omega_h t + \phi_h) + \Phi(t)) \end{aligned} \quad (1)$$

9 where A is the DC level of the light from the optical source; B
10 represents the magnitude of the phase modulated signal; C is the
11 magnitude of the carrier signal; ϕ_c is the phase of the carrier
12 signal; D is the magnitude of the signal of interest or measured
13 signal; ϕ_h is the phase of the signal of interest or measurand
14 signal; and $\Phi(t)$ is the time varying phase shift (or noise) due
15 to environmental effects, such as temperature variations and
16 mechanical stimulation, on the optical paths or fibers of the
17 interferometer sensor. The term $D \cos(\omega_h(t))$ represents the
18 signal of interest to be recovered from the phase modulated
19 signal $f(t)$ using quadrature sampling demodulation, as will be
20 described in greater detail below.

1 Both the carrier and measurand signals are represented in
2 the phase modulated signal $f(t)$, as shown graphically by the
3 frequency spectrum 40, FIG. 2, of the phase modulated signal
4 $f(t)$. The frequency spectrum 40 of the phase modulated signal
5 $f(t)$ includes multiple quadrature carrier frequencies f_c , $2f_c$,
6 $3f_c$, $4f_c$, ... (where $f = \omega/2\pi$) with sidebands 42 around each of the
7 carrier frequencies. The sidebands 42 represent spectral
8 frequencies of the measurand signal and its harmonics, which are
9 spaced from the respective carrier frequencies f_c by integral
10 multiples of the modulating frequency f_h of the measurand signal.

11 After the phase modulated signal $f(t)$ is photodetected, the
12 phase modulated signal $f(t)$ is received by the digital receiver
13 system 10 for sampling and for demodulating the phase modulated
14 signal $f(t)$ to recover the signal of interest $D\cos(\omega_h(t))$. The
15 phase modulated signal $f(t)$ is undersampled at a sampling rate
16 lower than the minimum sampling rates used in previous systems,
17 as disclosed in a related application to the same inventors, with
18 the same filing date (Attorney Docket No., Navy Case No. 77556)
19 entitled A DEMODULATION SYSTEM AND METHOD FOR RECOVERING A SIGNAL
20 OF INTEREST FROM AN UNDERSAMPLED, MODULATED CARRIER, incorporated
21 herein by reference.

1 As discussed above, previous systems used sampling rates of
2 at least twice the highest carrier frequency to accurately
3 reconstruct the phase modulated carrier signal. However, only
4 the sidebands 42 of the phase modulated signal need to be
5 accurately reconstructed by sampling to recover the measurand
6 signal. The sampling rate f_s must therefore be at least twice
7 the bandwidth Δf_h of the signal of interest or measurand signal,
8 which is significantly less than the carrier frequency f_c .

9 According to the present invention, the undersampling is
10 performed using quadrature time samples such that the sampling
11 also demodulates the phase modulated signal by producing odd and
12 even sampled signal components that represent the sidebands 42,
13 as will be described in greater detail below. The digital
14 receiver system 10 (FIG. 1) includes a quadrature sampling
15 demodulator 32 for sampling and demodulating the phase modulated
16 signal to produce the odd and even sampled signal components.
17 The digital receiver system 10 further includes circuitry 34, as
18 will be described in greater detail below, for completing the
19 demodulation process and recovering the signal of interest or
20 measurand signal $D\cos(\omega_h(t))$ from the odd and even sampled signal

1 components, for example, by normalizing and performing a
2 differentiate and cross-multiply (DCM) process.

3 The following mathematical representation of the
4 demodulation process illustrates how the measurand signal is
5 recovered from the phase modulated carrier signal $f(t)$. The
6 phase modulated signal $f(t)$ can be represented mathematically as
7 a Bessel series with the amplitudes of the carrier and sidebands
8 determined by Bessel functions. Setting the carrier phase ϕ_c and
9 measurand phase ϕ_h to be zero, the Bessel expansion of the phase
10 modulated signal $f(t) = A + B \cos(C \cos \omega_c t + \theta(t))$, where
11 $\theta(t) = D \cos \omega_h t + \Phi(t)$, is as follows:

$$12 \quad f(t) = A + B \left\{ \begin{aligned} & \left[J_0(C) + 2 \sum_{k=1}^{\infty} (-1)^k J_{2k}(C) \cos 2k \omega_c t \right] \cos \theta(t) \\ & - \left[2 \sum_{k=0}^{\infty} (-1)^k J_{2k+1}(C) \cos(2k+1) \omega_c t \right] \sin \theta(t) \end{aligned} \right\} \quad (2)$$

13 where $\cos \theta(t)$ and $\sin \theta(t)$ represent the sidebands 42, which can
14 be represented through another Bessel expansion:

$$15 \quad \cos \theta(t) = \left[J_0(D) + 2 \sum_{k=1}^{\infty} (-1)^k J_{2k}(D) \cos 2k \omega_h t \right] \cos \Phi(t) \\ - \left[2 \sum_{k=0}^{\infty} (-1)^k J_{2k+1}(D) \cos(2k+1) \omega_h t \right] \sin \Phi(t) \quad (3)$$

$$16 \quad \sin \theta(t) = \left[2 \sum_{k=0}^{\infty} (-1)^k J_{2k+1}(D) \cos(2k+1) \omega_h t \right] \cos \Phi(t) \\ + \left[J_0(D) + 2 \sum_{k=1}^{\infty} (-1)^k J_{2k}(D) \cos 2k \omega_h t \right] \sin \Phi(t) \quad (4)$$

1 Thus, Bessel expansion equation (2) includes the odd and
2 even Bessel terms of the carrier, i.e., ω_c and $2\omega_c$. The terms
3 $\cos\theta(t)$ and $\sin\theta(t)$, as shown by the Bessel expansion equations
4 (3) and (4), include the odd and even Bessel terms of the
5 measurand signal, i.e., ω_h and $2\omega_h$. The phase term $\Phi(t)$ in
6 equations (3) and (4) determines if the odd or even Bessel terms
7 (or both) of the measurand signal are carried around the odd or
8 even Bessel terms of the phase generated carrier, as represented
9 in equation (2).

10 According to the preferred embodiment of the present
11 invention, the quadrature carriers f_c and $2f_c$ (or ω_c and $2\omega_c$) are
12 used to recover the signal of interest by extracting the
13 sidebands 44-47, FIG. 3, centered around the quadrature carriers
14 f_c and $2f_c$. Where only the quadrature carriers f_c and $2f_c$ are
15 used, the Bessel expansion in equation (2) can be reduced by
16 setting $k=0$ and $k=1$ as follows:

17
$$f(t) = -2BJ_2(C)\cos 2\omega_c \cos\theta(t) - 2BJ_1(C)\cos\omega_c t \sin\theta(t) \quad (5)$$

18 The amplitudes of the quadrature carriers are preferably
19 equalized to ensure minimal distortion of the reconstructed
20 signal. The amplitude of the quadrature carriers, as represented
21 by the odd and even terms in the Bessel series, are equalized by

1 adjusting the level of phase modulation. In other words, the
 2 magnitude C of the carrier is varied by adjusting the modulation
 3 of the optical source 14, for example, through external modulator
 4 19. When the amplitudes in the Bessel expansion of equation (5)
 5 are equalized, i.e., $J_2(C)=J_1(C)$, the odd and even Bessel terms
 6 are given as follows, where $k=-2BJ_2(C)=-2BJ_1(C)$:

$$7 \quad f_{\omega_1}(t) = k \cos \omega_c \sin \theta(t) \quad (6)$$

$$8 \quad f_{\omega_2}(t) = k \cos 2\omega_c t \cos \theta(t) \quad (7)$$

9 To recover the measurand signal, the sidebands 45, 47
 10 centered around the carriers f_c and $2f_c$, as shown in FIG. 3, are
 11 moved to the baseband, as shown in FIGS. 4 and 5 respectively.
 12 According to previous demodulation methods, the sidebands are
 13 basebanded by multiplication of the phase modulated signal $f(t)$.
 14 The quadrature sampling according to the present invention is
 15 mathematically similar to a multiplication that results in the
 16 sidebands being moved to the baseband. The effect of moving the
 17 sidebands to the baseband by multiplying the odd and even terms
 18 in equations (6) and (7) by $\cos \omega_c t$ is shown as follows:

$$19 \quad \begin{aligned} &= k \cos^2 \omega_c t \sin \theta(t) \\ &= \frac{k}{2} \sin \theta(t) + \frac{k}{2} \cos 2\omega_c t \sin \theta(t) \end{aligned} \quad (8)$$

$$\begin{aligned}
 &= k \cos^2 2\omega_c t \cos\theta(t) \\
 &= \frac{k}{2} \cos\theta(t) + \frac{k}{2} \cos 4\omega_c t \cos\theta(t)
 \end{aligned}
 \tag{9}$$

The term $(k/2)\sin\theta(t)$ in equation (8) represents the basebanded sidebands 45 shown in FIG. 4, and the term $(k/2)\cos\theta(t)$ in equation (9) represents the basebanded sidebands 47 shown in FIG. 5. Thus, the sidebands 45, 47 of ω_c and $2\omega_c$ are no longer located about ω_c and $2\omega_c$ but are now located in the baseband. The measurand signal can then be reconstructed from the basebanded sidebands 45, 47, i.e., $(k/2)\sin\theta(t)$ and $(k/2)\cos\theta(t)$.

The quadrature sampling demodulator 32 demodulates the phase modulated signal $f(t)$ and extracts the sidebands by using quadrature sampling periods that produce odd sampled signal components $(\cos\theta(t))$ and even sampled signal components $(\sin\theta(t))$. The sidebands around the quadrature carriers (or odd and even terms in the Bessel expansion) are in quadrature or 90° out of phase. Taking samples at a time period of t and a time period of t plus a quadrature time shift of Δt will extract the orthogonally related sidebands. The time shift of Δt provides for the quadrature phase shift of the sidebands around the even term (ω_{c2}) relative to the sidebands around the odd term (ω_{c1}) and

1 is equal to a time period of one quarter of a cycle of the
 2 carrier, i.e. $\Delta t = .25/f_c$ where $f_c = \omega_c/2\pi$.

3 The sampling rate f_s can thus be less than the carrier
 4 frequency f_c such that the quadrature sampling periods are
 5 represented as m/f_c and $m/f_c + \Delta t$, where $m \geq 1$, and where the
 6 sampling rate $f_c/m \geq 2\Delta f_h$. The sampling period of m/f_c recovers
 7 the odd terms and the quadrature sampling period, $m/f_c + \Delta t$,
 8 recovers the even terms. Sampling according to this method thus
 9 produces quadrature time sample pairs in which the odd harmonics
 10 are contained in an array of samples 1, 3, 5... taken at $t = m/f_c$
 11 while the even harmonics are contained in an array of samples 0,
 12 2, 4... taken at $t + \Delta t = (m + .25)/f_c$.

13 This process produces the functions shown in equations (10)
 14 through (13) for time samples $t = 1, 2, 3, 4...$ The odd time
 15 samples 1, 3, 5, ... taken at the sampling period of m/f_c are
 16 represented with the following equation:

$$17 \quad f_{\omega_{c1}}(t) = B \cos(C \cos(2m\pi f_c(t/f_c) + \phi_c) + D \cos(2m\pi f_h(t/f_c) + \phi_h) + \text{Phi}(t)) \quad (10)$$

18 The even time samples 0, 2, 4, ... taken at the sampling
 19 period of $m/f_c + \Delta t$ are represented with the following equation:

$$20 \quad f_{\omega_{c2}}(t) = B \cos(C \cos(2m\pi f_c(t + \Delta t)/f_c + \phi_c) + D \cos(2m\pi f_h(t + \Delta t)/f_c + \phi_h) + \text{Phi}(t)) \quad (11)$$

1 Simplifying equations (2) and (3) demonstrates how the
 2 carrier is shifted to the baseband, as a DC component:

3
$$f_{w_{ct}}(t) = B \cos(C \cos(2\pi + \phi_c) + D \cos(2\pi f_h t / f_c + \phi_h) + \text{Phi}(t)) \quad (12)$$

4
$$f_{\omega_2}(t) = B \cos(C \cos(2\pi(t + \Delta t) + \phi_c) + D \cos(2\pi f_h(t + \Delta t) / f_c + \phi_h) + \text{Phi}(t)) \quad (13)$$

5 According to one example, the sampling rate f_s of the
 6 present invention is selected to be the same as the carrier
 7 frequency f_c such that $t = 1/f_c$ and $t + \Delta t = 1.25/f_c$. An example
 8 of sampling in a previous oversampled system would have a
 9 sampling rate f_s of $8f_c$. The following table illustrates a
 10 comparison between the time samples taken using the previous
 11 method and the quadrature sampling of the present invention:

$t = 1/8f_c$	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
$t = 1/f_c,$ $1.25/f_c$	0	1							2	3							4	5

12 Sampling according to the present invention provides spacing
 13 between the quadrature time sample pairs, allowing time to
 14 multiplex additional sensors from a single optical source. The
 15 undersampling using the quadrature sampling period, thereby
 16 allows higher channel count systems with higher bandwidth sensors
 17 because fewer time samples are required to reconstruct the data.
 18 Undersampling also reduces the number of samples that must be
 19 processed. The undersampled demodulated signal also does not

1 contain spectral data outside of the modulated bandwidths of the
2 carriers, eliminating the need for low pass filtering.
3 Undersampling further eliminates the need for gain matched and
4 phased locked local oscillators for demodulating the odd and even
5 carriers to extract the sidebands.

6 In an interferometer sensor system having multiple sensors,
7 the phase delay ϕ_c will vary from sensor to sensor. The phase ϕ_c
8 is a function of the spacing of the sensors 20 relative to the
9 photodetector 22 and determines the magnitude B of the phase
10 modulated signal. This term does not have a time variable,
11 because the spacing between multiple elements is fixed. The
12 amplitude of B, due to the difference in the phase delays of the
13 sensors, requires channel gains to be trimmed to present a common
14 channel to channel sensitivity. The preferred embodiment of the
15 digital receiver system 10, FIG. 2, includes a gain adjuster 36
16 for adjusting and matching the gain(s) in the odd and even
17 channels to present a common channel to channel sensitivity.

18 Once the gains of the odd and even channels have been
19 matched, the measurand signal $D\cos(\omega_h(t))$ is determined from the
20 odd and even sampled signal components $\cos\theta(t)$ and $\sin\theta(t)$, for
21 example, using conventional circuitry 34 for normalizing and

1 performing a differentiate and cross-multiply process (DCM). One
2 example of normalizing includes calculating the square root of
3 the sum of the squares and dividing. The normalized odd and even
4 terms can be processed using either a conventional analog or a
5 digital differentiate and cross-multiply technique.

6 According to one alternative of the present invention, the
7 time shift Δt is set. This removes the need for equalizing the
8 amplitude of the quadrature carriers. The magnitude of the phase
9 modulated signal is detected and normalized to one before the
10 phase modulated signal is sampled. The step of normalizing the
11 signals (i.e., calculating the square root of the sum of the
12 squares and dividing) prior to the DCM process can thus be
13 eliminated. The magnitude and phase distortions caused by
14 unequalized quadrature carriers is also eliminated.

15 Accordingly, the digital receiver system of the present
16 application recovers a measurand signal from a phase modulated
17 signal by undersampling and demodulating the phase modulated
18 signal using quadrature time samples. By sampling using
19 quadrature time samples, the rate of undersampling can be as low
20 as two times the bandwidth of the sensor's modulation, thereby
21 permitting higher sensor bandwidth and a larger number of

1 channels because fewer time samples are required to reconstruct
2 the data. Using the digital receiver system of the present
3 invention to demodulate the phase modulated signals also provides
4 a higher dynamic range, lower electronic noise, simplified
5 operation and repeatable performance from channel to channel as
6 compared to previous analog receiver systems.

7 In light of the above, it is therefore understood that
8 the invention may be practiced otherwise than as specifically described.
9

1 Navy Case No 77268

2

3 SYSTEM AND METHOD FOR RECOVERING A SIGNAL OF INTEREST
4 FROM A PHASE MODULATED SIGNAL USING QUADRATURE SAMPLING

5

6 ABSTRACT OF THE DISCLOSURE

7 A digital receiver system is used to recover a signal of
8 interest, such as a measurand signal, from a phase modulated
9 signal detected from a system utilizing quadrature carriers, such
10 as a fiber optic interferometer sensor system. The digital
11 receiver system includes a quadrature sampling demodulator that
12 samples the phase modulated signal by using quadrature sampling
13 periods to recover the odd and even components of the signal of
14 interest. The digital receiver system can be used with an
15 interferometer sensor system having an array of sensors that
16 multiplex the measurand signals, e.g., using time or wavelength
17 division multiplexing. Sampling with quadrature time samples
18 provides a spacing in time between the samples that allows
19 additional sensors to be multiplexed.

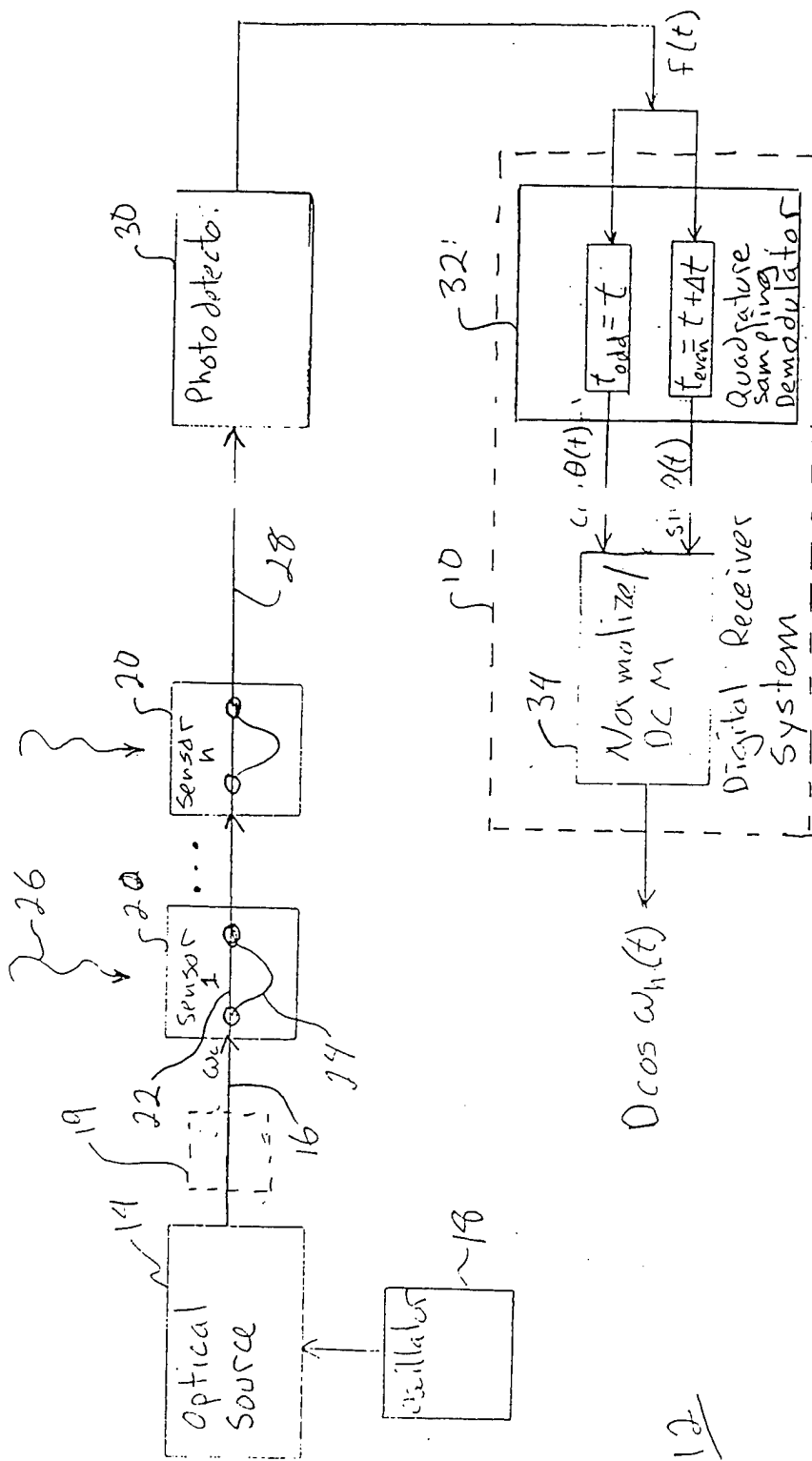


FIG. 1

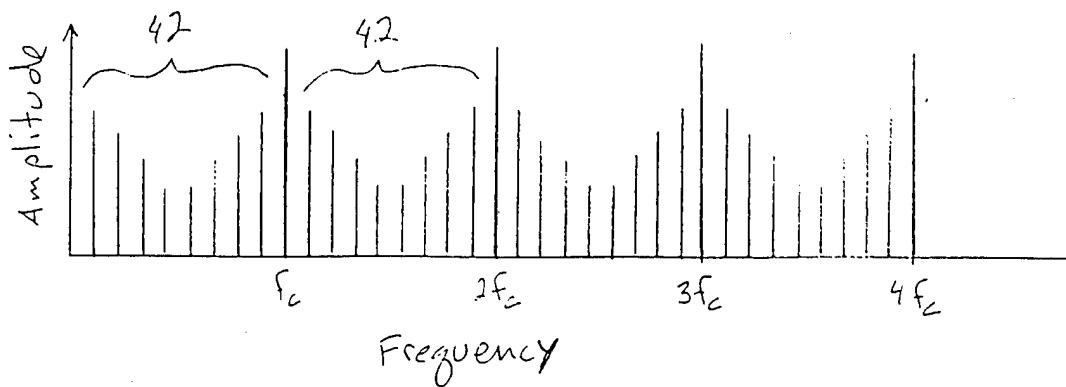


FIG. 2

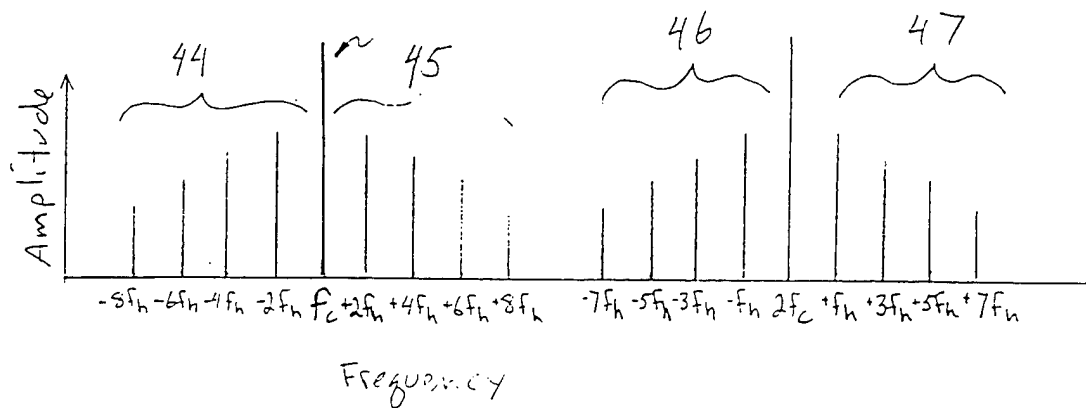


FIG. 3

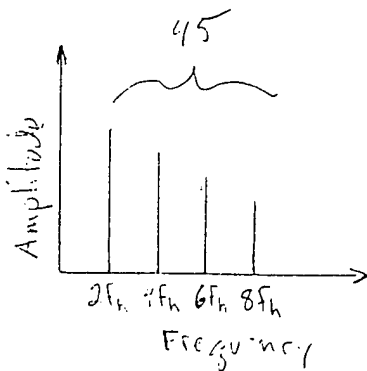


FIG. 4

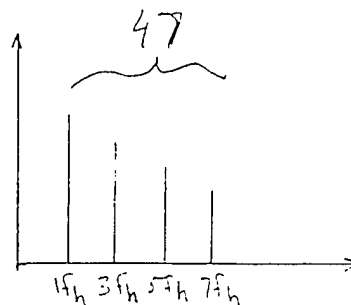


FIG. 5

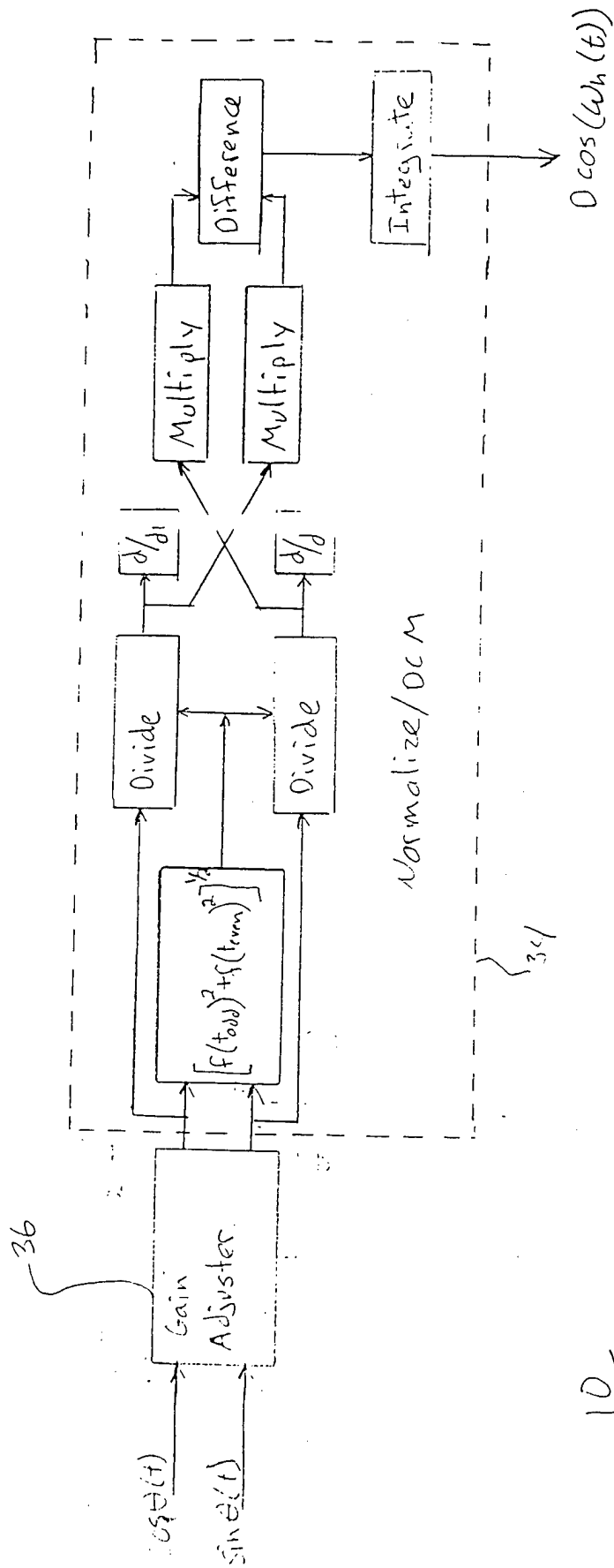


FIG. 6