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(71) Demandeur/Applicant:
HONEYWELL INTERNATIONAL INC., US

(72) Inventeurs/Inventors:
STRANDJORD, LEE K., US;
SANDERS, GLEN A., US

(74) Agent: GOWLING LAFLEUR HENDERSON LLP

(54) Titre : DISPOSITIF ANTI-BRUIT D'INTENSITE RELATIVE POUR SOURCES LUMINEUSES A FIBRES OPTIQUES
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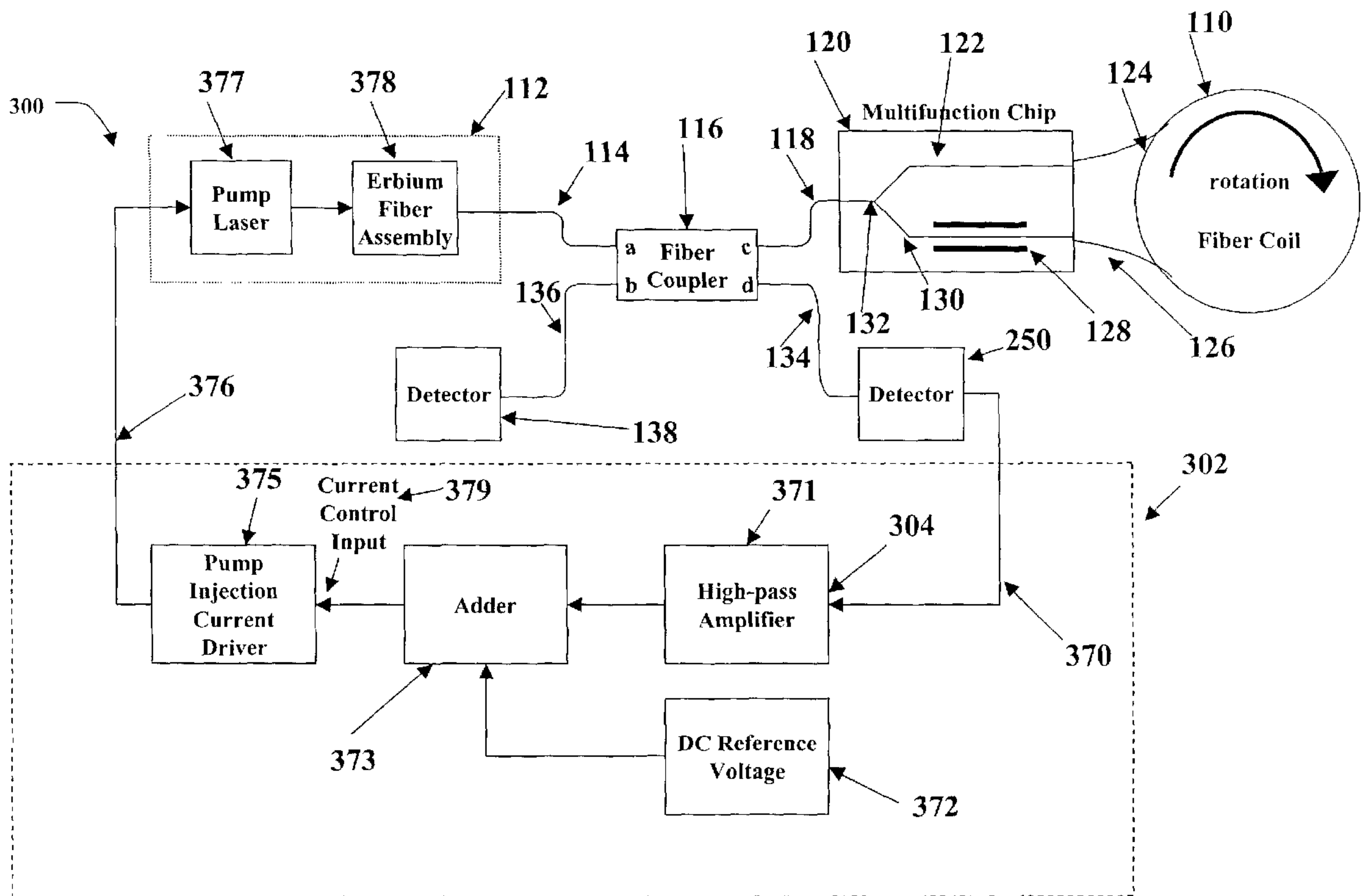

(57) Abrégé/Abstract:
A system and method is provided which suppresses relative intensity noise in a fiber optic gyroscope, by taking advantage of the frequency response of erbium fiber. In operation, the gain provided by the erbium fiber is added to the gain of the other components in the feedback loop to provide for stable loop performance up to about 250 kHz. The frequency response of the erbium fiber of about 3 kHz also provides a 6db per octave roll-off, which when used in a negative feedback control loop for controlling the current flowing to the gyroscope light source. THis, in turn, allows for a relative intensity noise control loop with a bandwidth much greater than 3 kHz, which may be used in high performance gyroscope applications.

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(71) Applicant: HONEYWELL INTERNATIONAL INC. [US/US]; 101 Columbia Road, P.O. Box 2245, Morristown, NJ 07960 (US).

(72) Inventors: STRANDJORD, Lee, K.; 35 Hillcrest Drive, Tonka Bay, MN 55331 (US). SANDERS, Glen, A.; 11034 N. 23rd Drive, Phoenix, AZ 85029 (US).

(74) Agents: CRISS, Roger, H. et al.; Honeywell International Inc., 101 Columbia Road, P.O. Box 2245, Morristown, NJ 07960 (US).

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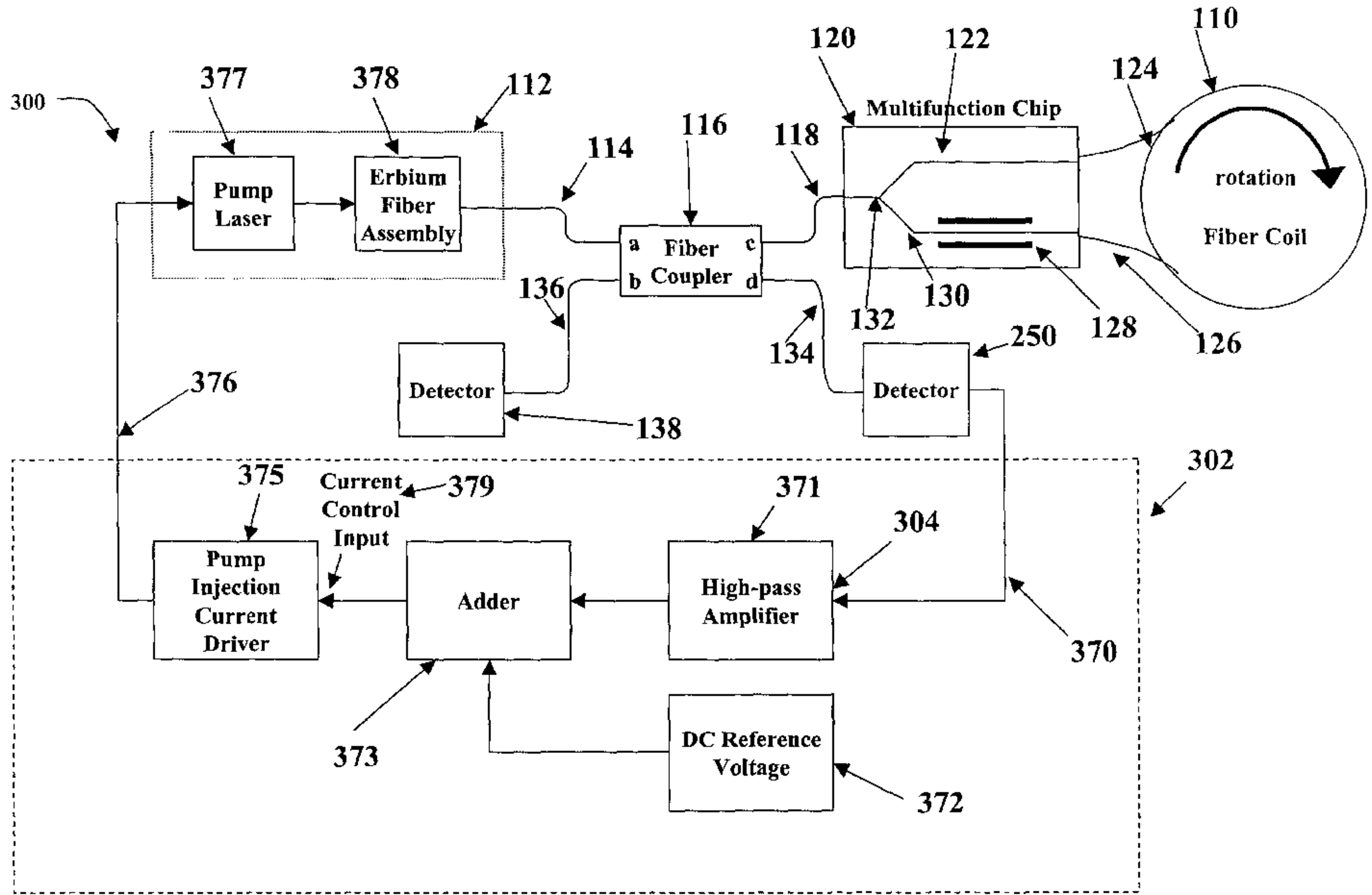

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RELATIVE INTENSITY NOISE CONTROLLER FOR FIBER LIGHT SOURCES

BACKGROUND OF THE INVENTION

1. Field of the Invention:

This invention generally relates to fiber optic gyroscopes, and methods of making and operating fiber optic gyroscopes.

2. Description of the Related Art:

Fiber-optic gyroscopes are included in a powerful class of sensors which bring to measurement systems many of the advantages that optical-fiber technology has brought to communications systems. For example, the very high bandwidth of optical fibers used in fiber optic gyroscopes allows the fiber optic gyroscope to convey a large amount of measurand information through a single fiber. In addition, because optical fiber is a dielectric, it is not subject to interference from electromagnetic waves that might be present in the sensing environment. Further, fiber-optic gyroscopes typically can function under adverse conditions of temperature and pressure, and toxic or corrosive atmospheres that generally erode metals at a rapid rate.

The problem inherent in many conventional fiber optic gyroscopes, however, is that they can be sensitive to excess noise disturbances at low rotation rates. For example, the well known Raleigh scattering (i.e., scattering of light due to inhomogeneities in material density smaller than a wavelength in size), polarization noise (i.e., polarization fluctuations observed via voltage fluctuations), and zero rotation drift due to the Kerr effect (i.e., the development of birefringence when an isotropic transparent substance is placed in an electrical field) are typical problems which often reduce the accuracy of the optical gyroscope output by introducing errors in rotation rate sensing.

To minimize the errors in rotation rate sensing resulting from excess noise disturbances, fiber optic gyroscope system designers typically use broadband optical sources in gyroscope system construction. More particularly, fiber optic gyroscope designers typically use broadband optical sources with a stable spectra, such as, for example, super luminescent diodes (SLDs) or super luminescent fiber sources (SLSs), etc. The downside to using these sources, however, is that due to their finite bandwidth, these broadband sources introduce an additional excess noise term into the gyro output. This, in turn, causes a reduction in performance and satisfaction of the fiber optic gyroscope systems. It is, therefore, desirable to eliminate the excess noise component introduced by the broadband source in the gyro output to achieve optimum gyroscope performance.

Unfortunately, where SLDs are implemented in fiber optic gyroscopes, the fiber optic gyroscope generally suffers from a high wavelength sensitivity to temperature, inefficient coupling to single-mode fibers, and a lack of immunity to optical feedback. Consequently, in recent years, fiber optic gyroscope designers have focused less on fiber optic gyroscope systems using SLDs and more on super luminescent fiber sources (SLSs), which do not typically exhibit most of the problems inherent in the SLDs.

For example, where SLSs are used the fiber optic gyroscope will have a more stable response over temperature ranges inside the SLS spectrum. That is, the temperature stability of the SLS spectrum, in particular, its center wavelength, is far superior to that of the SLDs, whose emission wavelength typically varies by about 0.05 nm/deg C. Further, by designing with a SLSs the fiber optic gyroscope designer is capable of generating more power in a SLS than is available in an SLS. For example, in a typical SLD, the available power is approximately 30 mW, of which probably no more than a few milliwatts can be coupled to a single mode fiber. On the other hand, where a typical SLS is used, the fiber optic gyroscope designer is capable of generating approximately 40mW to 200mW of power. Further still, in a practical system, unwanted spurious reflections from the source/system interface can greatly reduce the power which can be coupled to the system fiber. These reflections can be minimized in the SLS fiber device by splicing the source and system fibers with a fused glass-to-glass splice, which typically can not be realized with SLDs. Finally, the high conversion efficiency of the SLS fiber source and its broad character pump band make SLSs a beneficial choice over SLDs for many compact, laser-diode-pumped configurations.

Super luminescent fiber sources (SLSs), typically consist of a single-mode fiber, with a core doped with an ionictrivalent rare earth element, such as model HG980 from Lucent Technologies in Chesterfield, Missouri, a pump laser such as FLD148G3NL-S from Fijitsu of Japan, and a wavelenth division multiplexer (WDM) such as model WS1415-LW from JDS Uniphase in Bloomfield, Connecticut. SLS's are well known in the art, and have been advantageously used to provide broadband (e.g., on the order of 10-30 nanometers) laser-like (highly directional) light beams for multiple applications, particularly in the communications field. For a description of an exemplary super luminescent fiber sources, see an article entitled "Amplification of Spontaneous Emission in Erbium-Doped Single-Mode Fibers," by Emmanuel Desuvrie and J. R. Simpson, published by IEEE, in "Journal of Lightwave Technology," Vol. 7, No. 5, May 1989, incorporated herein by reference.

As noted, a SLS typically includes a length of single-mode fiber, with a core doped with an ionic trivalent rare earth element. For example, neodymium (Nd^{3+}) and erbium (Er^{3+}) are rare earth elements that may be used to dope the core of a single-mode fiber so that the core acts as a laser medium. During operation, the fiber receives a pump input signal at one end, which is provided by a pump laser. The pump input signal is typically a laser signal having a specific wavelength λ_p. The ions within the fiber core absorb the input laser radiation at wavelength λ_p so that electrons in the outer shells of these ions are excited to a higher energy state of the ions. When a sufficient pump power is input into the end of the fiber, a population inversion is created (i.e., more electrons within the ions are in the excited state than are in the ground state), and a significant amount of fluorescence builds up along the fiber in both directions. As is well known, the fluorescence (i.e., the emission of photons at a different wavelength λ_s) is due to the spontaneous return of electrons from the excited state to the ground state so that a photon at a wavelength λ_s is emitted during the transition from the excited state to the ground state. The light which is emitted at the wavelength λ_s from the fiber is highly directional light, as in conventional laser light. One main characteristic of this emission which makes it different from that of a traditional laser (i.e., one which incorporates an optical resonator), however, is that the spectral content of the light emitted from the super luminescent fiber sources is generally very broad (between 1 and 30 nanometers). Thus, the optical signal output by the fiber will typically be at wavelength λ_p + about -15 nanometers.

The construction and operation of conventional fiber optic gyroscopes is well known, and as such, will not be discussed in detail herein. A typical discussion of fiber optic gyroscopes may be found in U.S. Patent No. 5,465,149 issued November 7,1995 to Strandjord, et al., and incorporated by reference herein. For illustrative purposes, Fig. 1 illustrates an exemplary fiber optic gyroscope system 100, which may be found in the prior art. In general, the optical portion of the system 100 contains several features along the optical paths to assure that this system is reciprocal. That is, when considering the system, it should be understood that substantially identical optical paths occur for each of the opposite direction propagating electromagnetic waves except for the specific introductions of non-reciprocal phase difference shifts, as will be described below. In general, the features along the optical paths include a fiber optic light source 112, a fiber coupler 116, a multifunctional processing chip (e.g., integrated optics chip) 120, and a fiber optics coil 110, which are all variously connected by optical fiber portions 114, 118, 124 and 126.

Coiled optical fiber forms a coil 110 about a core or spool using a single mode optical fiber wrapped about the axis around which rotation is to be sensed. The use of a single mode fiber allows the paths of the electromagnetic or light waves to be defined uniquely, and further allows the phase fronts of such a guided wave to also be defined uniquely. This greatly aids maintaining reciprocity.

Light source 112 may be any broadband light source for propagating electromagnetic waves through the fiber optics system 100. This source 112 is typically a semiconductor super luminescent diode or a rare earth doped fiber light source which provides electromagnetic waves near the infrared part of the spectrum, over a range of typical wavelengths between 830 nanometers (nm) and 1550 nm. In general, source 112 will have a short coherence length for emitted light to reduce the phase shift difference errors between these waves due to Rayleigh and Fresnel scattering at scattering sites in coil 110.

Between light source 112 and fiber optic coil 110 there is shown an optical path arrangement formed by the extension of the ends of the optical fiber forming coil 110 to some optical coupling components which separate the overall optical path into several optical path portions. As shown, optical fiber portion 114 is positioned against light source 112 at a point of optimum light emission therefrom, and, additionally, extends to a first optical directional coupler 116 (also referred to as a optical light beam coupler or wave combiner and splitter), wherein the optical fiber portion 114 ensures that light source 112 and coupler 116 are in constant communication.

Coupler 116 has light transmission media therein which extend between four ports a, b, c, and d, which are shown on each end of coupler 116. As can be seen, port a is connected to light source 112 via optical fiber 114 positioned thereagainst. At port b, on the sense end of optical directional coupler 116 there is shown a further optical fiber 136 which extends to be positioned against a photodetector 138.

Photodetector 138 detects electromagnetic waves, or light waves, impinging thereon from optical fiber portion 136 positioned there against and provides a photo current in response to a signal component selection means (not shown). This photocurrent, as indicated above, in the case of two nearly coherent light waves impinging thereon, follows a raised cosine function in providing a photocurrent output which depends on the cosine of the phase difference between such a pair of substantially coherent light waves. This photodetector device will operate at a very low impedance to provide the photo current which is a linear function of the impinging radiation, and may typically be a p-i-n photodiode.

Also positioned against coupler 116 is an optical fiber 134, which may typically not be used in the operation of the gyroscope. Abutting against port c of coupler 116 is yet another optical fiber 118 extending to multifunctional integrated optics chip 120, including a phase modulator 128, and integrated optics waveguides 122 and 130 which form a y-junction 132. Leading from multifunctional processing chip 120 are optical fibers 124 and 126, which are connected to fiber coil 110 via waveguides 122 and 130 respectively.

Between port b of fiber coupler 116 and the gyroscope output are various photosensitive and electrical components designed to sense and generate an output corresponding to the rotational speed of fiber coil 110. In particular, included are a photodetector 138, a analog signal conditioning device 140, an analog to digital converter (A/D) converter 142, a digital demodulator 144, and a square wave bias modulator 146, wherein each element is maintained in electrical communication during the processing of the fiber optic gyroscope system output. It should be noted that the function of each of the aforementioned elements is well known in the art. Consequently, the elements will be discussed below only briefly to aid in the understanding of the operation of the fiber optic gyroscope system 100.

Optical directional coupler (e.g., fiber coupler) 116, in receiving electromagnetic waves, or light, at any port thereof, transmits such light so that approximately half of the transmitted light appears at each of the two ports of the coupler 116 on the end thereof opposite that end having the incoming port. On the other hand, no such waves or light is transmitted to the port which is on the same end of coupler 112 as is the incoming light port. For example, light received at port a will be transmitted to ports c and d, but not to port b. Similarly, light received at port c will be transmitted to ports a and b, but will not be transmitted to port d, and so on.

Therefore, during operation, light source 112 transmits a broadband light wave to port a of coupler 116 via optic fiber 114. Fiber coupler 116 splits the transmitted light and provides the light to ports c and d, where the light provided to port d typically may not be used by the gyroscope. The light provided to port c, however is further transmitted to multifunctional integrated optics chip 120 via optic fiber 118, where the light wave is further split at y-junction 132 and provided to waveguides 122 and 130.

The light provided to waveguide 122 is transmitted to fiber coil 110, via optic fiber 124, where it propagates clockwise around the length of fiber coil 110 (hereinafter, "the cw wave"). Similarly, the light wave in waveguide 130 is provided to fiber coil 110 via optic fiber 126, where the light wave propagates counterclockwise around the length of fiber coil 110 (hereinafter, "the ccw wave").

After being transmitted from fiber coil 110 to multifunctional integrated optics chip 120 via optic fibers 124 and 126, respectively, the ccw and cw wave are combined at y-junction 132 before being further provided to port c of fiber coupler 116 via optic fiber 118. As noted above, once the two light waves are provided to port c, the waves are then provided to ports a and b, but not provided to port d.

Port b is further connected to photodetector 138 via optic fiber 136 such that the ccw and cw light waves are received at the photodetector 138, which in turn, provides an output photocurrent i to analog signal conditions unit 140. The value of photocurrent i is proportional to the intensity of the two electromagnetic waves or light waves impinging thereon. Therefore, the photocurrent i is expected to follow the cosine of the phase difference between the two waves which impinging on the detector 138.

In the prior art arrangement depicted, the output signal from photodetector 138 may be converted to a voltage and amplified at analog signal conditioning unit 140 (ASC). The output voltage signal may then be further provided to an analog to digital converter 142 where it is converted to a digital signal prior to being passed to PSD/digital demodulator 144. PSD/digital demodulator 144, serving as part of a phase demodulation system, is a well known device. Such a PSD/digital demodulator 144 extracts the amplitude of the fundamental frequency f_b of the photodetector 138 output signal, or the fundamental frequency of modulation signal generator 146 plus higher odd harmonics, to provide an indication of the relative phase of the electromagnetic waves impinging on photodetector 138. This information is provided by PSD/digital demodulator 144, as the output of the gyroscope.

Typically, gyroscopic designers seeking to minimize excess noise (e.g., "relative intensity noise") employ techniques which seek to phase modulate the light counterpropagating within the fiber coil so that the working point for signal measurement is always in the characteristic range of maximum measuring signal change per rotation rate change. That is, designers seeking to maximize the sensitivity of the gyroscope to sensing angular rotations must consider the maximum modulation which can occur for a particular gyroscope configuration, in order to maximize the gyroscope's sensitivity. Various conventional relative intensity noise or excess noise suppression techniques are described in U. S. Patent No. 6,204,521 issued March 20, 2001 to Strandjord et al., and incorporated herein by reference in its entirety.

One type of excess noise reduction technique found in the prior art, called the "subtraction" technique, is illustrated with reference to Fig. 2, wherein like character references as that of Fig. 1 indicate similar components of similar operation. Unlike what is depicted in Fig. 1, the portion of the light source 112 directed to port d of coupler 116 is utilized. That is, the light signal which is directed to optical fiber portion 134 is further provided to a second photodetector 250, where the signal is converted into a second photocurrent. The second photocurrent generated by photodetector 250 is further provided to a variable gain amplifier 251, where it is amplified prior to being provided to an analog adder 253.

In similar manner, coupler 116 provides a light signal to a first photodetector 138 via port b and fiber optic fiber portion 136. First photodetector 138 then converts the signal into a first photocurrent which is then provided to analog adder 253. It should be understood that analog adder 253 may be any convention adder for combining analog signals. Therefore, at analog adder 253, the first photocurrent and second photocurrent are summed to produce a summed photocurrent for providing to ASC 116.

For ideal optical components, the excess noise observed at first and second photodetectors 138 and 250, respectively, is correlated. That is, for a fiber optic gyroscope operating with a bias modulation at the coil eigen frequency, the excess noise at photodetector 138 occurring at the eigen frequency including odd harmonics will be 180 degrees out-of-phase with the noise at photodetector 250 occurring at the same frequencies. Therefore, by adding a properly gain adjusted signal from photodetector 250 to the signal from photodetector 138, the noise at the output of the adder 253 associated with excess noise will be reduced to zero at the eigen frequency and odd harmonics for a gyro employing ideal components. However, imperfections in real optical components such as polarization crosstalk will limit how much the excess noise is actually reduced.

An additional disadvantage of the "subtraction" technique is that, in order to have a high level of excess noise reduction, the amplitude adjustment of the signal from photodetector 250 must be relatively accurate. In particular, the amount of amplitude adjustment depends on many system parameters such as, the responsivity of photodetectors 138 and 250, the gain of the amplifier 251, the bias modulation amplitude and optical loss in the wave propagating path from fiber coupler 116 through multifunction chip 122 and fiber coil 110 and back through the fiber coupler 116 to photodetectors 138 and 250. Moreover, it is important to note that these system error in amplitude adjustment will increase as the system parameters change over time with the aging of the gyro.

The change in system parameters becomes even more pronounced in systems employing high performance fiber optic gyroscopes such as, for example, space applications which are exposed to radiation or submarine navigation applications which encounter an aging mechanism in the coil fiber that causes increased optical loss over time. (This aging mechanism is not well understood at this time.) In those systems, the amplitude adjustment made on the signal from detector 250 must typically be updated in order to track the drift which often readily occurs with regard to the noted system parameters. Consequently, the updating of the parameters is typically done by using a variable gain amplifier where the gain control 252 is adjusted based on a ratiometric measurement of the light detected at the photodetectors 138 and 250. As should be understood, the variable gain amplifier and circuits used to perform the ratiometeric measurements adds undesirable complexity to the design and operation of the gyroscope.

It should be noted, however, that the disadvantages inherent in the "subtraction" technique may typically be overcome by implementing an excess noise servo. In general, employing an excess noise servo typically involves providing a portion of the superfluorescent fiber light source to the servo, which in turn, uses the provided light to control the light source pump current (e.g., negative feedback). In this way, the light output intensity of the superfluorescent fiber light source becomes a function of the pump current, such that, random fluctuations in the intensity of the light output may be cancelled by applying the appropriate changes in pump current levels.

It should be further noted, however, that where a high performance fiber optic gyroscope used erbium fiber, it was believed that using the subtraction technique with servo control was impracticable. That is, it should be understood that the typical bias modulation frequency f_b of conventional high-performance fiber optic gyroscopes may be around 20kHz to 50kHz. In addition, one skilled in the art will understand that the fundamental demodulation frequency of a conventional high-performance fiber optic gyroscope may be the same as the bias modulation frequency. As shown by equation (1) below, the demodulator output noise depends on the input noise at the fundamental frequency and odd harmonics. Therefore, a careful inspection of equation (1) reveals that to reduce the effect of excess noise on angle random walk, the excess noise is typically reduced at the demodulation frequency fundamental, 3rd and 5th harmonics.

$$\sigma_{out} = R_f G_A B \sqrt{\sum_{i=0}^{\infty} \left(G_f \left[(2i+1) f_b \right] \frac{1}{2i+1} i_n \left[(2i+1) f_b \right] \right)^2} \quad . \qquad (1)$$

For high performance erbium fiber optic gyroscopes, however, it was believed that reducing the excess noise of the gyroscopic system at the demodulation fundamental, 3rd and 5th harmonics was impracticable because the upper state lifetime of the erbium fiber (e.g., erbium atoms) would limit how fast the output light could be controlled. That is, heretofore fiber optic gyroscope designers thought that after about 100 hertz, the frequency response of the erbium fiber would be ineffectual for controlling the excess noise output of the gyroscope via the pump current. Moreover, it was believed that the light output of the erbium fiber light source couldn't be controlled fast enough to manage intensity variations in the 20kHz to 50kHz range. Further, the designers believed that the bandwidth within which an excess noise servo could operate in a system using erbium doped optical fiber would be limited to less than 100 Hz.

Recent experimentation on the frequency response of erbium fiber, however, has yielded different and unexpected results. Namely, it was discovered that an examination of the frequency response of the erbium fiber after the cutoff frequency was suitable for use in fiber-optic gyroscope technology, in that the roll off after the cutoff frequency permitted increased control of the relative intensity noise servo. For example, it was discovered that after the cut-off frequency of the erbium fiber a pump intensity of about 1480 nm provided to a 1550 nm erbium fiber intensity had a 3 kHz frequency response and that after the 3kHz cutoff frequency, the intensity rolloff of the pump erbium fiber combination was a manageable 6db/octave. Consequently, it was discovered that the unexpected characteristics of the erbium fiber allows construction of a relative intensity noise servo with a bandwidth of at least 100KHz to 500kHz. This, in turn, provides a noise reduction realization of a factor of 4 at the output of the fiber optic gyroscope demodulator.

Until now, the use of the properties of the erbium fiber to enhance the gain in the fiber optic system has gone untried because of the errant belief that the relatively long upper-state life-time of the erbium atoms would limit any control of light intensity to well below 1kHz.

Looking into it. (Lee, please provide cites to written sources which support this assertion.)

Hence, a need exist for a system for use in reducing the excess noise of gyroscopic system at the demodulation fundamental, 3rd and 5th harmonics which allows additional control of the angle random walk and relative intensity noise by capitalizing on the gain provided the gyroscope by the erbium fiber. Presently known control methods for controlling excess noise gyroscopes using erbium remain inadequate, particularly in their ability to limit excess noise and provide pump current control at low frequencies.

SUMMARY OF EXEMPLARY EMBODIMENTS OF THE INVENTION

Various embodiments of methods and systems are provided for reducing relative intensity noise in a high performance fiber optic gyroscope, which addresses many of the shortcomings of the prior art. More particular, various methods and systems are provided, herein, for reducing the excess noise present in a erbium-doped fiber optic gyroscope by manipulating the intensity of the light provided by a erbium-doped light source in response to the gain attributable to the gain characteristics of the erbium-doped fiber.

In accordance with various aspects, a system for suppression of relative intensity noise in a fiber optic gyroscope is provided, wherein the system takes advantage of the frequency response of a erbium fiber to control variations in pump current, and thus control fluctuations in the gyroscopic light source. In particular, various embodiments use the erbium fiber frequency response to facilitate a stable control loop feed back design for controlling the pump current. More particularly, the invention takes advantage of the recent discovery that the frequency response of erbium fiber above 3kHz mimics closely an integrator with a 6dB/octave rolloff, which allows for a relative intensity noise control loop with a bandwidth much greater than 3kHz. With this type of frequency response, a stable loop with positive gain in the frequency range of 20kHz to 200kHz, or higher, is provided.

In accordance with one exemplary aspect, a portion of the erbium fiber light source (e.g., "light signal") is provided to a photodetector for detecting the fluctuations in the light intensity of the erbium light source. The photodetector converts the light signal into an electrical signal prior to the signal being amplified. A constant direct current (dc) signal is impressed upon the amplified signal and then the combined signal is further provided to the current control input of a pump injection current driver, the output of which is the injection current supplied to the pump laser for conversion into optical power. The optical power is then provided to the erbium fiber light source which, in turn, causes the erbium fiber to emit light at a wavelength representative of a nominal intensity level.

In accordance with another aspect of the invention, the fluctuations in light intensity caused by the existence of excess noise or relative intensity noise is reduced via a control loop wherein the amount of reduction is a function of the open loop gain of the control loop. The open loop gain of the control loop is enhanced by the additional gain provided the loop due to the erbium fiber.

In accordance with yet another aspect of the invention a servo control is provided to facilitate the control of the intensity fluctuations of an erbium-doped light source in response to the gain to the overall system attributable to the erbium-doped light source.

BRIEF DESCRIPTION OF DRAWINGS

A more complete understanding of the present invention may be derived by referring to the various exemplary embodiments of the present invention which are described in conjunction with the appended drawing figures in which like numerals denote like elements, and in which:

Fig. 1 is a schematic block diagram of a prior art fiber optic gyroscope employing a digital demodulator;

Fig. 2 is a schematic block diagram of a prior art fiber optic gyroscope employing a "subtraction technique" for reducing excess noise.

Fig. 3 is a schematic block diagram depicting the use of a negative feedback to the pump laser for controlling light source intensity;

Fig. 4A-4B are Bode plots illustrating the open loop gain versus frequency of the major components that make up an excess noise control loop.

Fig. 5A-5B are Bode plots illustrating the open loop gain versus frequency of the major components that make up an excess noise control loop utilizing a lead lag circuit; and

Fig. 6A-6B are schematic diagrams of an alternate method for excess noise control loop utilizing a lead-lag circuit.

DETAILED DESCRIPTION OF VARIOUS EXEMPLARY EMBODIMENTS

The present invention may be described herein in terms of functional block components and various processing steps. It should be appreciated that such functional blocks may be realized by any number of hardware and/or software components configured to perform the specified functions. For example, the present invention may employ various integrated circuit or optical components, e.g., memory elements, processing elements, logic elements, look-up tables, and the like, which may carry out a variety of functions under the control of one or more microprocessors or other control devices. Similarly, where the elements o the present invention are implemented using software programming or software elements the invention may be implemented with any programming or scripting language such as C, C++, Java, assembler, or the like, with the various algorithms being implemented with any combination of data structures, objects, processes, routines or other programming elements. Further, it should be noted that the present invention could employ any number of conventional techniques for electronics configuration, optical configuration, signal processing and/or control, data processing and the like.

It should be further appreciated that the particular implementations shown and described herein are illustrative examples of the invention and are not intended to otherwise limit the scope of the invention in any way. Indeed, for the sake of brevity, conventional electronics, control systems, optics, software development and other functional aspects of the systems (and components of the individual operating components of the systems) may not be described in detail herein. Furthermore, the connecting lines, or connectors shown in the various figures contained herein are intended to represent exemplary functional relationships and/or physical or logical couplings between the various elements. It should be noted that many alternative or additional functional relationships, physical connections or logical connections may be present in a practical sensor device. Moreover, no item or component is essential to the practice of the invention unless the element is specifically described herein as "essential" or "critical".

Further while the invention is described herein in terms of high performance gyroscopes, it is to be understood that the invention is not so limited. For example, to facilitate the understanding of the invention, the invention may be described in terms of various conventional fiber optic systems such as, for example, temperature sensors, strain sensors and/or magnetometers or like sensors using erbium fibers. Typical gyroscope system technology which may benefit from this invention includes, for example, those gyroscopes described in U. S. Patent No. 5,767,968, issued June 16, 1998 to Strandjord, U. S. Patent No. 5,781,300 issued July

14, 1998 to Strandjord, et al., and U. S. Patent No. 5,999,304 issued December 7, 1999 to Sanders, et al. (all of which are incorporated herein by reference in there entirety), all of which are contemplated to be well within the scope of this invention.

According to various exemplary embodiments of the invention, a fiber optic sensor (and an associated method of operation) is produced that provides a highly reciprocal light path for two or more light beams in a gyroscope. Indeed, the paths taken by the various beams propagating through the optical portion of the sensor may be identical except for a portion of the optical circuit that induces a modulation between the beams. It will be appreciated that any of the various conventional techniques (such as manufacturing techniques, modulation techniques and signal processing techniques) that have been used in conjunction with interferometric sensors (such as interferometric fiber optic gyroscopes) may be used in conjunction with the present invention. Moreover, bulk optics components (couplers and the like) may be substituted for any of the components described herein in various alternate embodiments.

Further, while the exemplary embodiments are described, herein, with respect to various amplifiers, and various circuits which effect a higher gain and thus a more sensitive frequency response, it is to be understood that such circuitry may comprise any suitable controls for use in a feedback circuit.

It should be noted that with respect to the use of a servo for controlling excess noise, or relative intensity noise in a fiber optic gyroscope, the bandwidth of the servo, as determined by the frequency response to variations in pump power, was thought to be limited to about 3 kHz because of the presence of the erbium doped optical fiber included in light source 112. However as will be more fully described below, Figs. 4A, 4B, 5A and 5B illustrate a more accurate depiction of the erbium frequency response above 100 Hz. That is, as can be seen, the upper state life time of the erbium atoms has a far different response than was previously believed by gyroscope designers. In order to aid in the full understanding of the benefit of the recently discovered erbium frequency response, an exemplary fiber optic gyroscope system using erbium and employing a feedback loop for controlling light fluctuations will be described below with respect to the variously included Figs.

Fig. 3 is a block diagram of an exemplary embodiment of a fiber optic gyroscope (FOG) in which a fiber optic gyroscope system 300 includes negative feedback to the pump laser 377 via pump injector current driver 375. The technique of using "negative feedback," typically requires that part of the signal being produced by the fiber optic gyroscope is fed back and compared with the signal produced by the light source 112. In this way, distortions introduced into the fiber optic gyroscope system may typically be precorrected and largely eliminated. As a result, the fiber optic gyroscope system may be made almost distortionless, despite fluctuations in the power supply and performance of electronic components.

With respect to Fig. 3, an exemplary fiber optic gyroscope using a negative feedback 300 suitably includes a light source 112, a fiber optical coupler 116, a multifunctional integrated optical chip 120, a fiber coil 110, a first and second photodetector circuits 138 and 250, respectively, and a servo control 720. Servo control 720 further includes a frequency filter 371, a dc reference voltage 372, an adder (e.g., summer) 373, and a pump injection current driver 375. As can also be seen, light source 112 further includes a pump laser 377, and an erbium fiber assembly 378.

It should be noted that like elements as those described with reference to Figs. 1, 2 and 3, have similar construction and/or operation. In addition, photodetector 138 may be connected to any suitable system for providing a gyro output signal, such as the systems previously depicted with reference to Figs. 1 and 2, which may include various ASCs, A/D converters, modulators, demodulators, and the like. Moreover, light source 112 may be suitably coupled to fiber coupler 116, and fiber coupler 116 may be suitably coupled to photodetectors 138 and 250 in similar manner as was described with reference to Figs. 1 and 2. Further, fiber coupler 116 may be coupled to a multifunctional integrated chip including a y-junction 132, and to gyroscopic coil 110, via an optical fiber 118, as was also depicted in Figs. 1 and 2.

It should be noted that optical fibers (such as fibers 114, 118, 124, 126, 134 and 136) interconnecting the various components in fiber optic gyroscope system 100 may be any sort of optical fiber capable of directing light between the components. In various embodiments, the optical fibers are single mode fibers capable of directing a single optical mode such that various filters are not required in fiber optic gyroscope system 300 to isolate desired modes for signal processing. Optical fibers may also be polarization maintaining fibers, particularly in embodiments that do not include a polarizer in the optical circuit (such as the embodiment shown in Fig. 3). If polarization maintaining optical fiber is not used, various alternate embodiments might include an optical polarizer anywhere in the optical circuit such as in integrated optics chip 120 or between coupler 116 and optics chip 120.

Coupler 116 may be any coupling device capable of joining optical signals propagating on separate fibers. Exemplary couplers include conventional 2x2 couplers available from the Gould Electronics in Millersville, Maryland, as Model PM-10055-052UV01. Alternatively, fibers 114 and 136, and/or 118 and 134 may be joined to form a coupler by stripping the cladding off of each fiber in the relevant position for the coupler, placing the two fiber cores together, and melting the cores together with the application of heat and optional tensile pressure.

Multifunctional integrated optics chip (IOC) 120 suitably includes a y-junction 132 and at least one modulator 128. In various embodiments, multifunctional integrated optics chip 120 is formed from lithium niobate ($LiNO_3$) or another material that affects the speed of light in response to an applied electric potential. Alternatively, multifunctional integrated optics chip 120 may be any conventional optical splitter/modulator combination such as a model 10022250 available from the JDS Uniphase corporation of Bloomfield, Connecticut. Multifunctional integrated optics chip 120 suitably includes a waveguide (shown as solid lines in integrated optics chip 120) for guiding light from source 112 through the chip. The path may include a y-junction 132 that splits light from coupler 116 into two paths 122 and 130. Y-junction 132 may also re-combine light received upon paths 122 and 130, as appropriate. One or more optical phase modulators 128 (which may be implemented as electrodes in multifunctional integrated optics chip 120 near paths 122 and/or 130) may also be provided to produce phase shifts in light passing through paths 122 and 130, respectively, in response to modulation signals produced by phase modulator 128. In various alternate embodiments and as described more fully below, multifunctional integrated optics chip 120 may be replaced with different but equivalent components such as couplers, splitters, modulators (such as piezoelectric modulators) and the like.

Photodetector 250 is further connected to a negative feedback loop 302 for providing a pump laser error signal to light source 112 via an optical fiber 376. In one exemplary embodiment, feedback loop 302 suitably includes a high-pass amplifier 371 electrically coupled to a photodetector 250, a dc reference voltage 372, an adder 373 electrically coupled to high-pass amplifier 371 and dc reference voltage 372, and a pump injection current driver 375 electrically coupled to adder 373 and to light source 112. In accordance with various embodiments light source 112 may be of similar construction and operation as similar element described with respect to Fig. 1, wherein the light source includes a erbium fiber assembly 378 and a pump laser 377.

In accordance with various embodiments, high-pass amplifier 371 may be an operational amplifier with an input capacitor/resistor parallel combinations and a feedback resistor. DC reference voltage 372 may be any source capable of providing a suitable reference voltage (e.g. 2.5V) for adding to the output of high pass amplifier 371. For example, dc reference voltage 372 may be **I'll get pa part number of a reference voltage that comes in an IC dip package (Lee**

please provide specific constructions which would be suitable for providing a dc reference voltage to this system). Further, adder 373 may be any element capable of combining at least two electrical signals and providing a summed electrical signal. For example, adder 373, may be a digital or analog summer, such as, for example, two resistors with a common connection to a summing junction of an operational amplifier. Further still, pump injection current driver 375, may be any current driver capable of providing current signal to pump laser 377. A typical pump injection current driver for use with various embodiments may typically consist of an operational amplifier, a power transistor with several resistors and capacitors. Since the construction of a typical pump injection current driver is well known in the art, it will not be discussed in detail herein.

Light source 112 may be any typical light source employing erbium doped fiber assembly 378 and a pump laser 377 for controlling the intensity of the light emitted by the light source 112. A typical source for use with various embodiments is described in "Erbium-Doped Fiber Amplifiers", (John Wiley & Sons, Inc., NY) 1994, incorporated herein by reference.

In one exemplary embodiment, feedback loop 302 suitably may include any processing circuitry capable of receiving the output of photodetector 250 and calculating a feedback signal for providing to light source 112. For example, feedback loop 302 may include any conventional microprocessor, microcontroller, digital signal processor, programmed array logic (PAL), application specific integrated circuit (ASIC), any suitable signal filtering system, summer or injection driver, and the like, suitable for calculating fiber optic output and feedback signal.

In another exemplary embodiment, negative feedback loop 302 further includes a high-pass filtering system 371 coupled to photodetector 250 via electrical connector 370, and to an adder 373 via connector 304. Adder 373 is further connected to a system for providing a dc reference voltage 372 via connector 706, and to pump injection current driver 375 via connector

708. In addition, pump injection current driver 375 is further connected to the pump laser 377 of light source 112 via connector 376.

It should be noted that photodetectors 138 and 250 may be any circuit capable of detecting the intensity (i.e. amplitude) of light emanating from fibers 136 and 134. In various embodiments, photodetector circuits 138 and 250 suitably include a photodiode that conducts an electric current in response to the intensity of incident light. Photodetector circuits 138 and 250 may also include circuitry or other components to generate a digital or analog signal that is provided to any of an ASC 138, amplifier 251, or the like, as appropriate. Numerous conventional photodetector circuits 138 and 250 have been developed for use with fiber optic gyroscopes or other sensors that may be applicable to sensor 100. In various embodiments, photodetectors 138 and 250 may consist of FET transistors, an operational amplifier, resistors and capacitors, and a photodiode. An example of a photodiode which may be used with this invention includes model EXT300T available from JDS Uniphase of West Trenton, New Jersey. Photodetectors 138 and 250 response may be dependent upon the wavelength of incident light. Consequently, photodetectors 138 and 250 may be selected to correspond to the wavelength of light propagating through fiber optic gyroscope system 300.

It should be further noted that, various embodiments of signal feedback and filtering have been disclosed in conjunction with various fiber optic gyroscope devices, and any fiber optic gyroscope electronics scheme could be readily adapted for use in sensor 300. For example, system 300 may suitably integrate signal filtering and processing into photodetector 250 to produce a conditioned output signal. It should be appreciated that the embodiment shown in Fig. 3 may be operated in a feedback driven or "closed loop" configuration, as well as, an "open loop" (i.e., no feedback) configuration that generates a modulation signal without regard to the output of photodetector 250.

During operation, photodetector 250 provides an electrical signal representing the intensity of light impinging on the photodetector 250 to high-pass amplifier 371. High-pass amplifier 371 amplifies the electrical signal with a gain of unity to 100 prior to providing the signal to adder 373. The amount of gain depends on various factors such as the coupling ratio of the coupler 116, the voltage to current gain of the pump current driver 375 and the efficiency of the light source 112. DC reference voltage element 372 further provides a dc reference voltage of about 2.5V to adder 373. Adder 373 further sums the signals provided by the high-pass amplifier 371 and the dc reference voltage element 372, into a summed signal for providing to the pump injection current driver 375 via the current control input 379. The pump injection current driver 375 may typically convert the summed signal into a current signal for use in controlling the pump laser of light source 112.

The summed signal is further provided to the current control input 379 of pump injection current driver 375, where it is further provided to pump laser 377 of light source 112. The pump laser 377 generates an optical power which is provided to (e.g., "injected into") the erbium fiber of the erbium fiber assembly 378. The light from the pump laser 377 causes the erbium fiber to emit light at a wavelength that is different than that of the pump light. That is, the erbium fiber emits light whose wavelength is 1550 nm.

It should be understood that fluctuations in light intensity at detector 250 are reduced by gain of the control loop formed by the high-pass amplifier 371, adder 373, pump injection current driver 375, light source assembly 112, fiber coupler 116 and detector 250. Moreover, in a typical embodiment, the amount of reduction suitably depends in part on the open loop gain of the control loop. That is, the greater the open loop gain at a particular frequency, the greater the amount intensity fluctuations which are reduced at that frequency. This is in part because the higher loop gain increases the embodiments sensitivity to low frequency rotation such that the gyroscopic rotation may properly be evaluated with little signal fluctuation.

It should be noted that additional open loop gain, thus additional noise reduction, can be realized by employing a second-order negative feedback loop. Fig. 6A is a block diagram of another exemplary embodiment of a fiber optic gyroscope using negative feedback to pump laser 377 via pump injector current driver 375 and in which a second order negative feedback loop is used. As can be seen, the circuit depicted in Fig. 6A is substantially the same as the circuit shown in Fig. 3, such that like elements of Fig. 3 and Fig. 6A have substantially similar operation and performance. It should be noted, however, that Fig. 6A includes a lead-lag circuit 610 which may be positioned between the high-pass amplifier 371 and adder 373.

Lead lag circuit 610 may be of any conventional construction for allowing a stable feedback loop with higher loop gain, which results in more noise reduction above the circuit depicted in Fig. 3. Fig. 6B shows an exemplary lead-lag circuit for use with Fig. 6A, however, other suitable circuits may be used. In one particular embodiment, lead-lag circuit 610 may include a resistor 602 connected in parallel with a capacitor 603 and a load resistor connected to the negative terminal 605, of operational amplifier 604. The values of capacitor 603 and resistor 602 may be of suitably value for controlling the time constant of the circuit 610. For example, the values of the capacitor 603 and the resistor 602 may be chosen to suitably control the frequency response of the circuit 610 (e.g., time constant = resistor times capacitor).

The construction and operation of lead-lag circuits is well known. As such, the construction and operation of lead-lag circuit 610 will not be discussed herein in detail. It should be noted that, while the lead lag circuit 610 is depicted using discrete elements, the circuit 610 may be implemented using any suitable lead-lag circuitry, such as, for example, any integrated circuit, software implementation or the like.

As mentioned previously, gyroscopic designers have attempted to increase the bandwidth of the servo beyond 3kHz by increasing the overall gain of the loop to frequencies much greater than unity. Because it was thought, however, that increasing the gain past the current limits of an utilized current pump would saturate the pump with current noise, it was further believed that the bandwidth of the servo in a system using erbium fiber would be limited to about 100Hz. However, as is shown in Figs. 4A-B and 5A-B, the frequency response of the erbium fiber does not saturate the pump, but instead adds gain to the feedback system such that bandwidth of the servo is increased above 100Hz. This, in turn, provides for an increase in the level of open loop gain at frequencies higher than 3 kHz. That is, by taking advantage of the erbium frequency response, a high performance gyroscope designer may increase the gain of the overall feedback system, and thus allowing for greater circuit response to excess noise are or relative intensity noise.

Depicted in Fig. 4A-4B are typical Bode plots showing the open loop gain of a simple excess noise servo, such as the ones depicted in Figs. 3 and 6A-B. In particular, Fig. 4A depicts the gain which occurs during various stages of the control loop. For example, curve 460 is a typical bode plot of the gain of high-pass filter 371 used in the invention, which has a lower cutoff frequency of f_1 and an upper cutoff frequency of f_4, where f_1 may be from about 1Hz to 100Hz and f_4 may be from about greater than tens of megahertz. In addition, curve 461 is a typical Bode plot of the gain of the photodetector 250, which may typically have a low-pass cutoff frequency of f_3, which is typically from about greater than a few megahertz. Further, curve 462 is a Bode plot of an exemplary gain of the erbium fiber light source, which has a low-pass cutoff frequency of f_2, typically from about 1kHz to 3kHz.

As noted above, the frequency response of the erbium fiber is a function of the upper state life time of the erbium atoms, and further, as shown by curve 462, the erbium fiber frequency response is such that when combined with the frequency responses of the high-pass filter 371 and the detector 250, does not cause the pump laser to saturate with noise current. That is, as can be seen by curve 463 of Fig. 4B, which depicts the net (e.g., sum total) open loop gain of the simple excess noise control loop of Fig. 3, the frequency response of the erbium fiber suitably allows a loop gain roll-off of about 6dB/octave in the region of unity loop gain. Consequently, by including the gain attributable to the erbium fiber, the frequency response of the loop is made stable. Further, in typical gyroscope design using negative feedback to control the light source intensity, the loop gain may typically be limited such that the unity gain frequency is less than the cutoff frequency f_3 of photodetector 250. That is, since the photodetector 250 typically demonstrates a frequency roll-off at about f_3, the frequency response of the photodetector 250 with respect to the other electronic components in the feedback loop (e.g., adder pump injection current driver, high-pass filter and the like) will typically limit how much noise reduction is realized.

With respect to Figs. 5A-B, Bode plots show the open loop gain of the second-order feedback loop shown in Fig. 6A-B. In particular, Fig. 5A shows the gain of various stages of the control loop of Fig. 6A-B, such that curve 560 is a typical bode plot of the gain of high-pass filter 371 used in the invention, which has a lower cutoff frequency of f_1 (e.g., from about 1Hz to 100Hz) and an upper cutoff frequency of f_4 (e.g., from about greater than tens of megahertz). Further, curve 561 is a typical Bode plot of the gain of the photodetector 250, which may typically have a low-pass cutoff frequency of f_3 (e.g., from about greater than a few megahertz). Further still, curve 962 depicts a Bode plot of the gain of the erbium fiber light source, which has a low-pass cutoff frequency of f_2 (e.g., from about 1kHz to 3kHz). In addition, curve 520 is a typical Bode plot of the gain of the frequency response of the lead-lag circuit 610 shown in Figs. 6A-B. Further still, curve 521 of Fig. 5B is a typical bode plot of the over-all gain of the second-order control loop of Fig. 6A.

It should be understood that by introducing the lead-lag circuit 610, higher gain below the photodetector 250 cutoff frequency f_3 may be obtained. Since the frequency response of the feedback loop will be second order, the lead-lag circuit gives higher gain at lower frequency, but has a flat frequency response above f_6. As long as f_6 is chosen correctly, the flat frequency response ensures that the control loop remains stable. The lead-lag circuit does not increase gain between f_6 and f_3, but does increase gain below f_6. Moreover, by introducing the lead-lag circuit, there is a faster rise (12dB/octave) in gain with lower frequency below f_6 (e.g., from about 100 kHz to 1 MHz). One skilled in the art will recognize that the frequency f_6 depicts frequency where the roll-off the lead-lag circuit stops and is determined by the value of resistor 602 and the value of capacitor 603 in Fig. 6A, which offer the time constant of the lead-lag circuit in Fig. 6B (e.g., time constant=RxC). That is, after the frequency f_6 and through the unity gain frequency, the open loop roll-off is 6dB/octave, and therefore allows for a stable loop.

Fiber optic gyroscopes have been described above with reference to various exemplary embodiments. However, those skilled in the art will recognize that changes and modifications may be made to the exemplary embodiments without departing from the scope of the present invention. For example, the various operational steps, as well as the components for carrying out the operational steps, may be implemented in alternate ways depending upon the particular application and/or polarization state of the light source (e.g., polarize or unpolarized) or in consideration of any number of cost functions associated with the operation of the system, e.g., various of components may be deleted, modified, or combined with other components such as providing a detector with a suitable high-pass frequency response, or a frequency filter unit with a suitable high-pass, lead-lag response.

In addition, where the light source is polarized, the invention may be included in the fiber optic gyroscope system along with the structure necessary to support such polarization.

Further, it should be noted that while the relative intensity noise suppression system is described above is suitably for suppressing excess noise in a fiber optic gyroscope, the system may also be used in any system wherein it is beneficial to increase the over-all system loop gain by including the gain provided by an erbium fiber, such as for example, other fiber optic sensors that measure current, magnetic field, strain and pressure.

Further still it should be understood that while the gyroscopic system of the present invention has been described in an "open loop" gyro configuration, the invention is not to be so limited. For example, with the addition of electronics necessary to convert the signal at detector 138 to a rotation signal, the system herein may be described in a closed loop configuration. Such electronics may involve conventional methods for conditioning the signal at detector 138 and then providing a feedback signal to multifunction chip 120 to sum with the signal at detector 138. The amount of feedback provided may be a function of the rotation rate of the gyro. Conversion of an open loop gyroscopic system to a closed loop system is well understood and, as such, although contemplated to be within the scope of the this invention, the particulars of the conversion will not be discussed herein for brevity.

These and other changes or modifications are intended to be included within the scope of the present invention, as set forth in the following claims.

CLAIMS

We claim:

1. A system for suppression of relative intensity noise in a fiber optic gyroscope comprising:

an erbium-doped broadband light source for generating a light output, comprising a pump laser and a fiber assembly, said pump laser configured to provide a pumped laser signal to said fiber assembly for controlling the intensity of said light output;

a modulator for receiving said light output and generating an intensity modulated light by modulating light emitted from said light source;

a tap coupler for receiving said light output and sampling a part thereof to provide a first sampled signal, and for receiving said intensity modulated light and sampling a part thereof to provide a second sampled signal;

a first photodetector for sensing said first sampled signal and detecting the intensity thereof and converting said first sampled signal to first detected signal having a voltage proportional to the intensity of said first sampled signal;

a second photodetector for sensing said second sampled signal and detecting the intensity fluctuations of said second sampled signal;

a pump injection current driver for providing a control signal to said pump laser; and servo control, responsive to said first detected signal, said servo logic for generating an error signal to cause said pump injection current driver to provide an injection current signal to said pump laser for varying the pump laser signal provided to said fiber assembly thereby causing said light source to cancel out intensity fluctuations of the light output at said second photodetector, thereby suppressing said relative intensity noise, wherein said tap coupler, said first photodetector, said pump injection current driver, pump laser and said servo control comprise a feedback loop which utilizes negative feedback to control said intensity fluctuations, and wherein said servo control comprises a voltage amplifier having characteristics such that the open loop gain of said feedback loop is responsive to the gain provided by the erbium-doped broadband light source.

2. A system according to claim 1, wherein at least one of said first and second photodetector comprises a photodiode and a trans-impedance amplifier.

3. A system according to claim 1, wherein said servo control logic has a bandwidth of at least 200 kHz.

4. A system according to claim 1, wherein said fiber assembly comprises a polarizer.

5. A system according to claim 1, wherein said servo control further includes at least a second order feedback control logic.

6. A system for suppression of relative intensity noise in a fiber optic gyroscope comprising:

a erbium-doped broadband light source for generating a light output, said erbium-doped broadband light source configured to control the light fluctuations of said light output;

a tap coupler for receiving said light output and sampling a part thereof to provide a sampled signal;

a photodetector for sensing said first sampled signal and detecting the intensity fluctuations thereof and converting said sampled signal to a detected signal having a voltage proportional to the intensity of said first sampled signal; and

servo control, responsive to said detected signal, said servo control for generating an error signal to cause said erbium-doped light source to vary the intensity of the light output thereby causing said light source to cancel out intensity fluctuations of the light output, wherein said tap coupler, said photodetector, said erbium-doped light source and said servo control comprise a feedback loop which utilizes negative feedback to control said intensity fluctuations, and wherein said servo control has the characteristics such that the open loop gain of said feedback loop is responsive to the gain provided by the erbium-doped light source.

7. A system according to claim 1, wherein at least one of said first and second photodetector comprises a photodiode and a trans-impedance amplifier.

8. A system according to claim 1, wherein said servo control logic has a bandwidth of at least 200 kHz.

9. A system according to claim 1, wherein said fiber assembly comprises a polarizer.

10. A system according to claim 1, wherein said servo control further includes at least a second order feedback control logic.

11. A method for suppression of relative intensity noise in a fiber optic gyroscope comprising the steps of:

receiving a light output from an erbium-doped light source and sampling part of the light to provide a first sampled signal;

sensing said first sampled signal to provide a control signal representing the intensity of the light output;

varying the intensity of the light received from said light source in response to said control signal, to cancel out intensity fluctuations of the light and thereby suppress said relative intensity noise; and

amplifying said control signal to produce an error signal, wherein the step of varying said intensity of the light includes controlling a pump power signal provided to the erbium-doped light source such that the intensity of the light received from said light source is varied in accordance with said error signal, and wherein said intensity of said light is modulated at a rate responsive to the gain provided by the erbium doped light source.

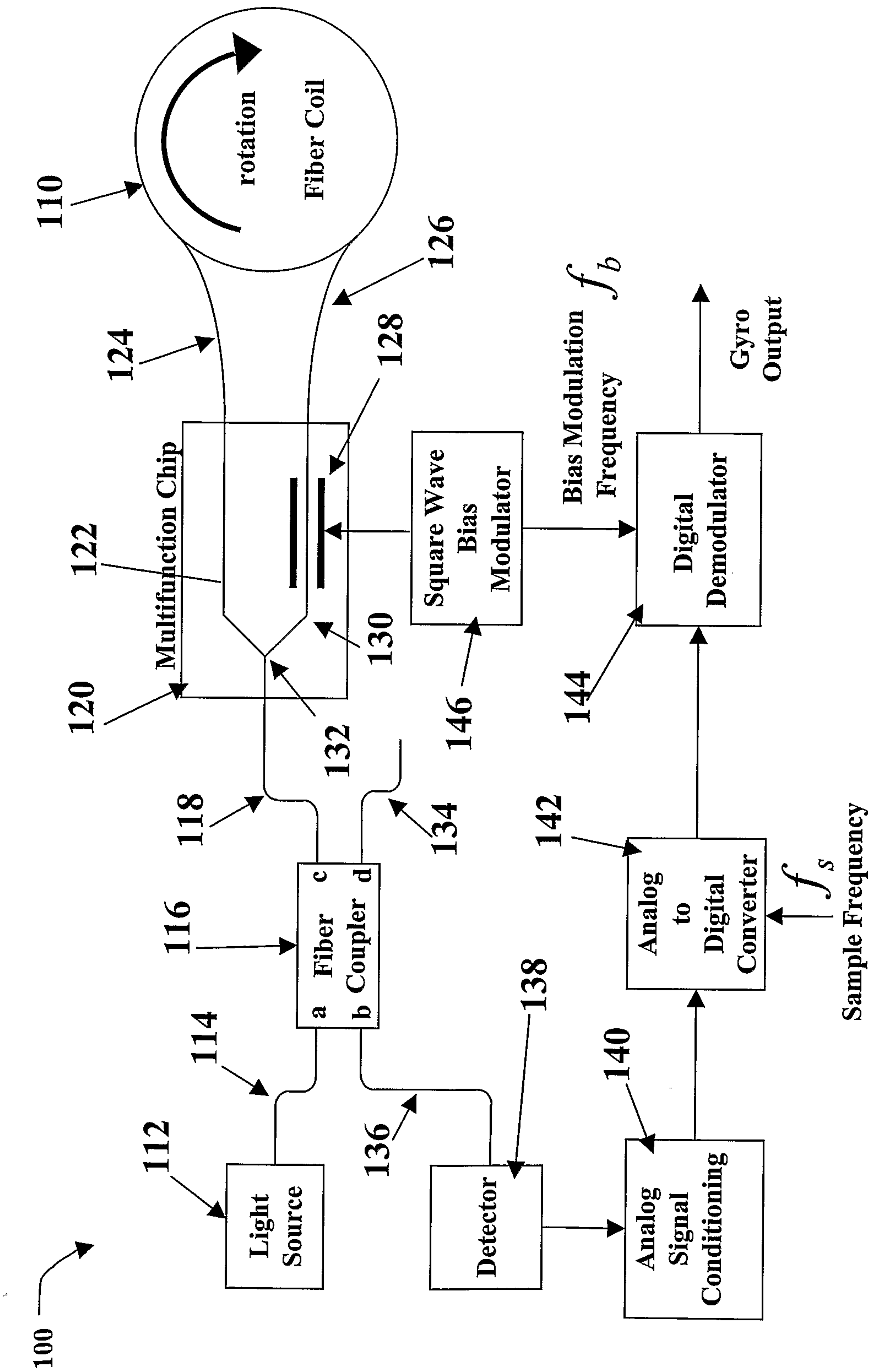


Fig. 1 PRIOR ART

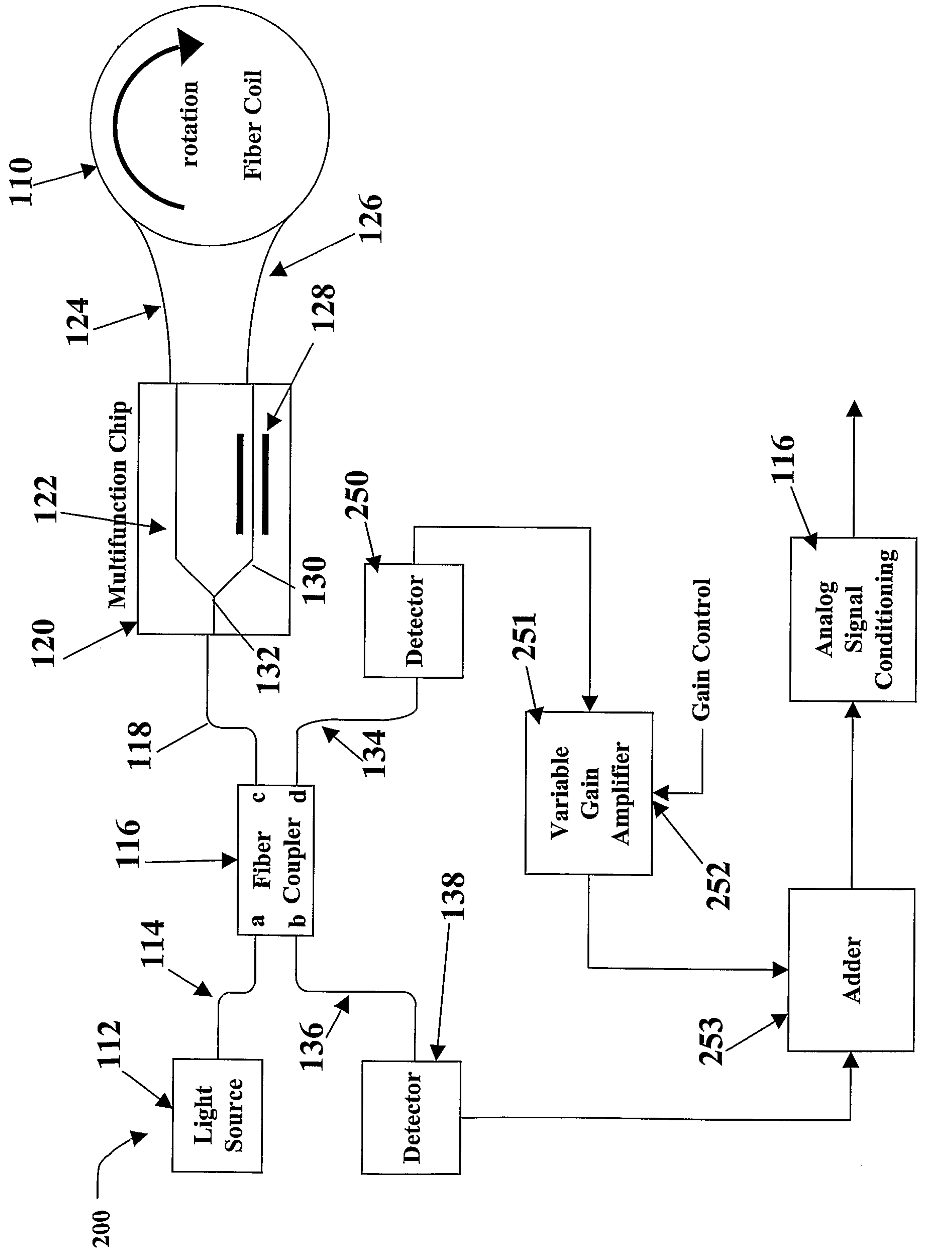


Fig. 2 PRIOR ART

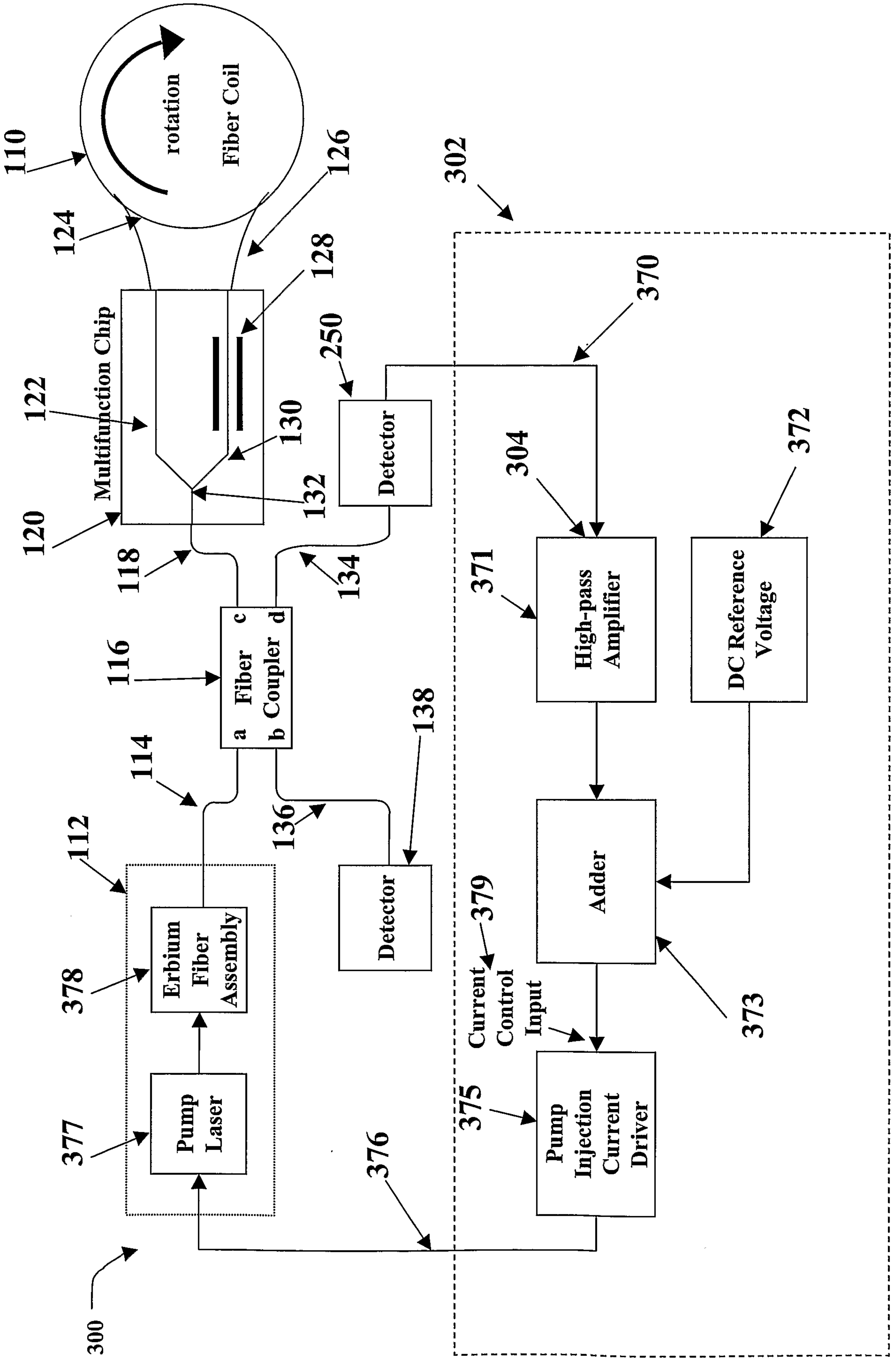

rotation
Fiber Coil
110
124
126
302
128
370
Multifunction Chip
250
122
Detector
130
304
372
132
120
118
134
371
High-pass Amplifier
DC Reference Voltage
116
a Fiber c
b Coupler d
114
138
136
112
Adder
379
Erbium Fiber Assembly
Detector
378
Current Control Input
373
375
Pump Laser
Pump Injection Current Driver
377
376
300

Fig. 3

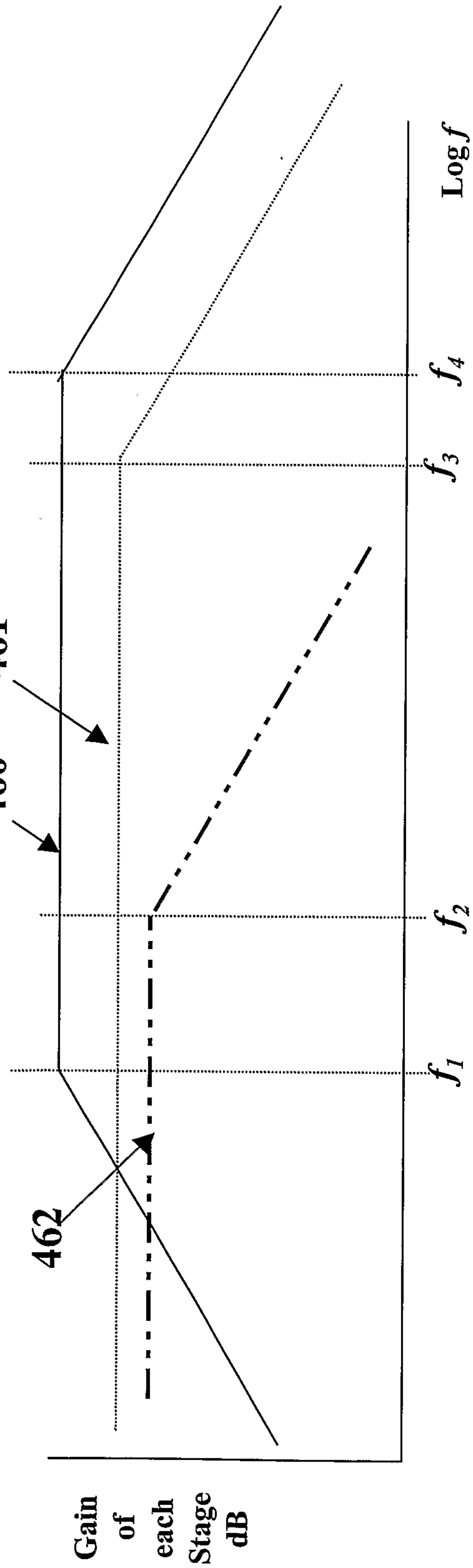

460
461
462
Log f
f1
f2
f3
f4
Gain of each Stage dB

Fig. 4A

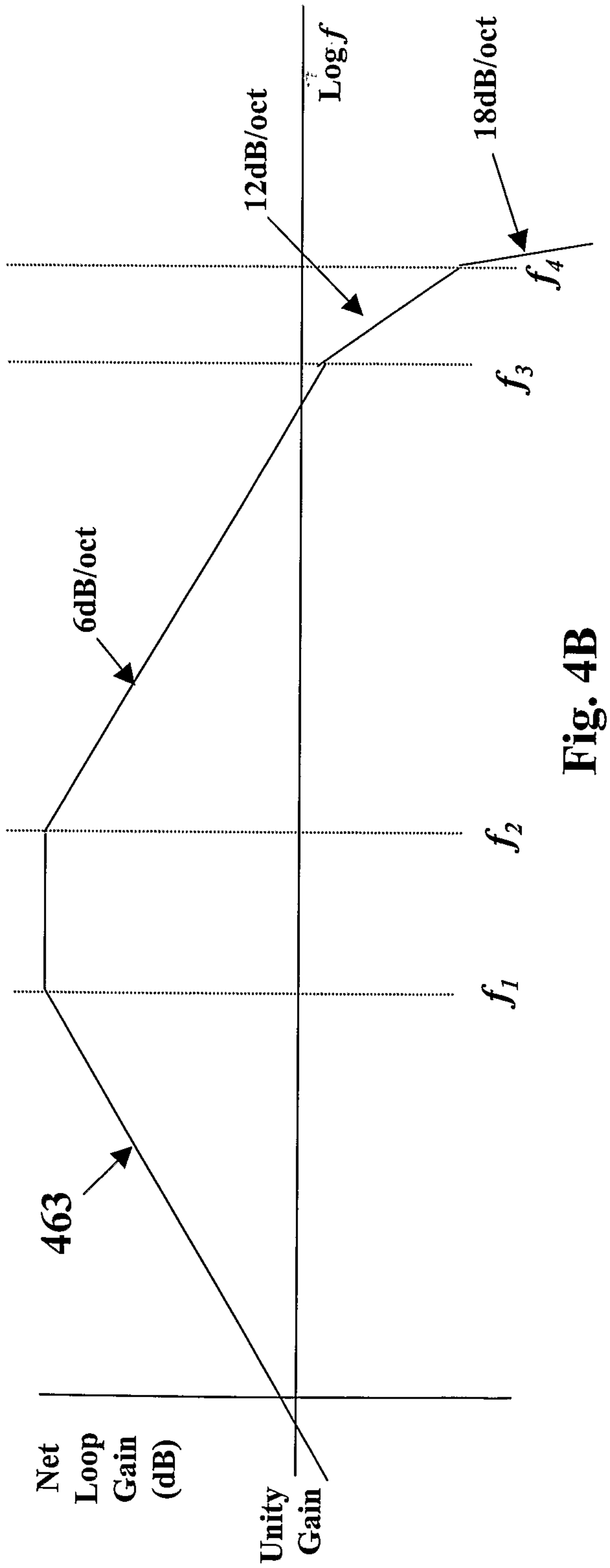

463
6dB/oct
12dB/oct
18dB/oct
Log f
f1
f2
f3
f4
Net Loop Gain (dB)
Unity Gain

Fig. 4B

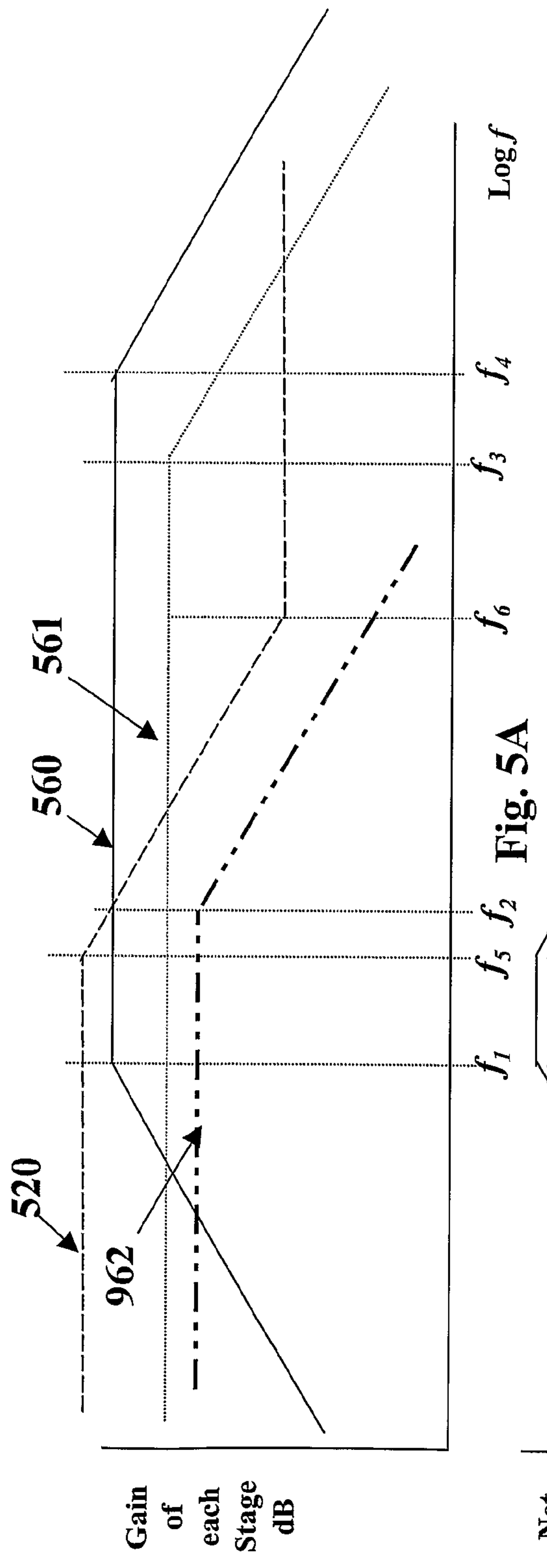

Gain of each Stage dB
520
962
560
561
f_1
f_5
f_2
f_6
f_3
f_4
Log f

Fig. 5A

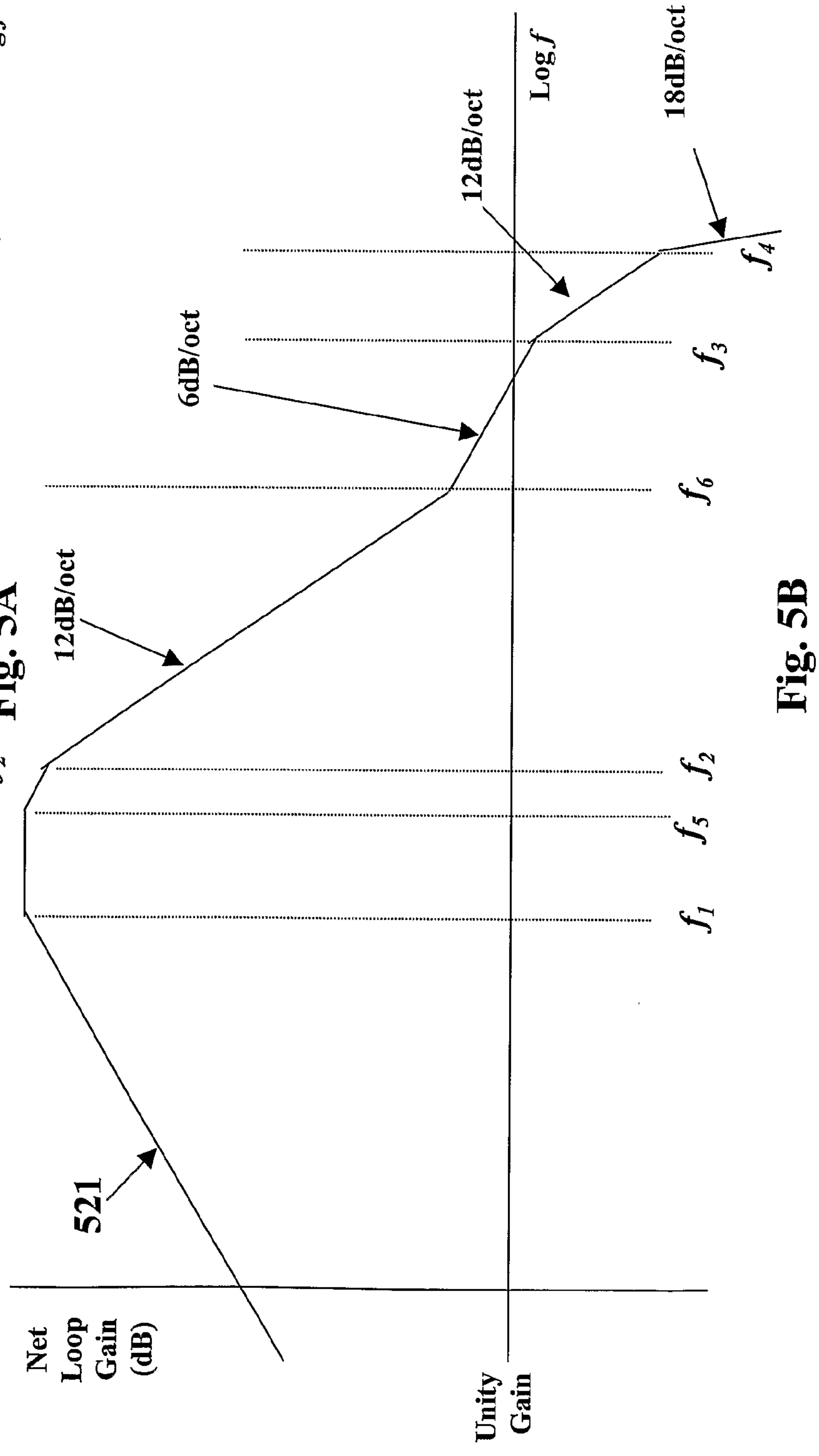
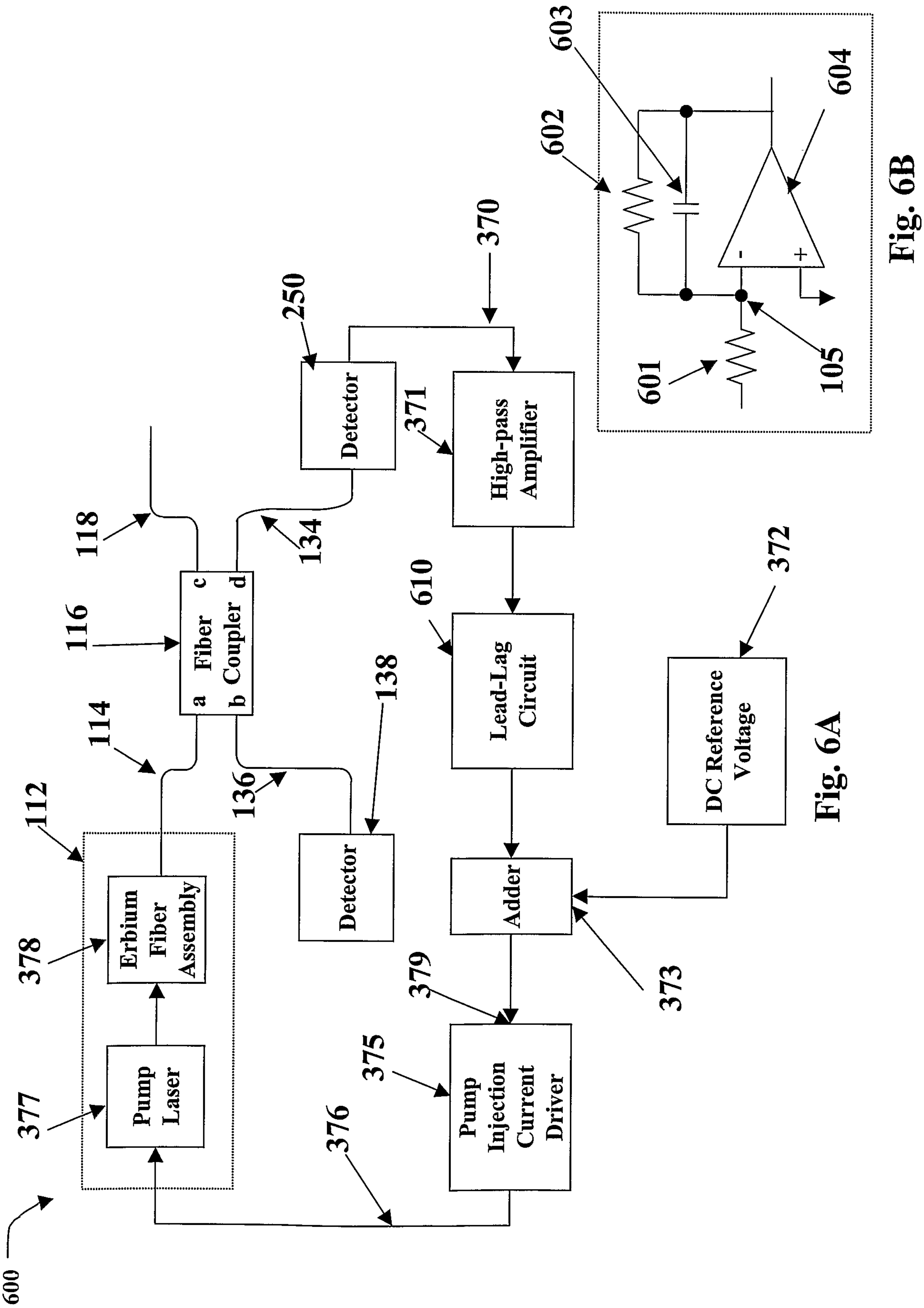

Net Loop Gain (dB)
Unity Gain
521
12dB/oct
6dB/oct
12dB/oct
18dB/oct
f_1
f_5
f_2
f_6
f_3
f_4
Log f

Fig. 5B


600
Pump Laser
377
Erbium Fiber Assembly
378
112
114
a b Fiber Coupler c d
116
118
134
136
Detector
138
Detector
250
370
High-pass Amplifier
371
Lead-Lag Circuit
610
Adder
373
DC Reference Voltage
372
379
Pump Injection Current Driver
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604
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Fig. 6A

Fig. 6B


300
377
378
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Pump Laser
Erbium Fiber Assembly
114
116
a
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b
d
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120
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