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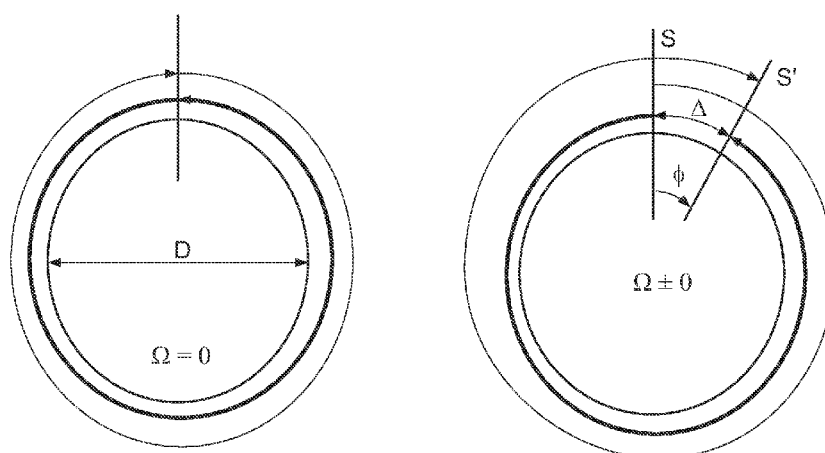
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(54) Title: OPTICAL SOURCE FOR INTERFEROMETRIC FIBER OPTIC GYROSCOPES

**FIG. 1**(57) **Abstract:** Optical source. The source includes a broadband, incoherent light source and a semiconductor optical amplifier in saturation arranged to receive light from the broadband incoherent light source to generate output light having reduced relative intensity noise. Following an optical source by one or more saturated semiconductor optical amplifiers provides a compact, efficient and low complexity RIN-suppressed optical source for an interferometric fiber optic gyroscope. The degree of RTN suppression (hence gyro noise reduction) is significant and is predicted to lead to as much as 20-30 dB gyro noise reduction.

OPTICAL SOURCE FOR INTERFEROMETRIC FIBER OPTIC GYROSCOPES

Sponsorship Information

5 This invention was made with government support under Contract No. FA8721-05-C-0002 awarded by the U.S. Air Force. The government has certain rights in the invention.

Background of the Invention

10 This invention relates to an optical source for an interferometric fiber optic gyroscope that has reduced relative intensity noise for enhanced gyroscopic performance.

 Fiber optic gyroscopes (FOGs) have numerous applications in navigation and pointing. Interferometric FOGs (IFOGs) use broadband light to sense rotation. The use of
15 broadband incoherent light, as opposed to lasers, has benefits in minimizing many error sources such as polarization crosstalk, backscattering, and optical nonlinearities such as the Kerr effect in the fiber sense loop. Conventional incoherent broadband optical sources, however, suffer from relative intensity noise (RIN) that limits the performance of the gyroscope. A RIN-reduced incoherent broadband optical source would be a key enabler for
20 high grade IFOG sensors overcoming the above limitations.

 Previous methods of RIN reduction include feed-forward [2], broadening of the optical source spectrum [3], modulation techniques [4], and electronic noise subtraction [5].

 In the feed-forward (FF) implementation, the power output of an optical source is sensed and fed forward to a fast variable optical attenuator (VOA) in order to limit optical
25 power fluctuations. The degree of fluctuation suppression (hence termed "reduced RIN") depends on the FF electronic gain and the time response of the optical power sensor and variable attenuator. Fluctuations below a certain characteristic frequency are suppressed which again depends on electronic gain and response of the optical power sensor and VOA. Although FF techniques work, they have the disadvantages of being bulky, power hungry,
30 and comparatively costly. All other methods demonstrated in the prior art offer limited RIN reduction of a few dB for IFOG applications.

Summary of the Invention

5 The optical source according to one aspect of the invention includes a broadband, incoherent light source and one or more semiconductor optical amplifiers in saturation arranged to receive light from the broadband, incoherent light source to generate output light having reduced relative intensity noise. In one preferred embodiment the broadband, incoherent light source is an erbium-doped fiber amplifier.

10 In another aspect, the invention is an interferometric fiber optic gyroscope including a broadband, incoherent light source. A semiconductor optical amplifier in saturation is arranged to receive light from the broadband, incoherent light source to generate output light having reduced relative intensity noise. A fiber sense coil receives counter-propagating
15 beams of the output light from the semiconductor optical amplifier and an optical detector is provided that is responsive to an interference fringe from which rotation rate is determined.

Brief Description of the Drawing

20 Fig.1 is a schematic illustration of the operation of a Sagnac loop. The loop on the left is non-rotating and on the right, the loop is rotating at an angular rate.

 Fig.2 is a schematic illustration of a conventional prior art interferometric fiber optic gyroscope (IFOG) in minimum configuration.

25 Fig.3 is a graph showing angle random walk (ARW) contributions from shot noise, thermal and RIN noise plotted against detected optical power.

 Fig.4 is a graphical illustration showing the impact of a reduced RIN source on angle random
30 walk.

 Fig.5 is a schematic illustration of an embodiment of the invention in which a broadband source is directed into a semiconductor optical amplifier.

Fig.6 is a graph illustrating the high pass filtering behavior of a semiconductor optical amplifier.

Figs.7a and 7b are schematic illustrations of an experimental setup for RIN measurement.

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Fig.8 is a graph of RIN suppression versus input power showing RIN reduction of an EDFA, a source used in the prior art.

Fig.9 is a graph of angle random walk versus optical power on a photodetector showing angle random walk as a function of optical power received by the gyroscope photodetector.

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Description of the Preferred Embodiment

IFOGs sense rotation based on the Sagnac effect. Briefly, the Sagnac effect is a phase shift that occurs between two counterpropagating electromagnetic waves in a ring interferometer when the interferometer is rotating. For a circular coil of diameter D and fiber length L, the Sagnac shift is given by $\Omega \cdot (2\pi LD)/c\lambda$, where c is vacuum speed of light, λ is the vacuum optical wavelength corresponding to the frequency centroid of the broadband source, and Ω rotation rate as shown in Fig1. The $(2\pi LD)/c\lambda$ term is called Sagnac gain and is a measure of gyro sensitivity to rotation. The main takeaway from the Sagnac gain expression is that IFOG sensitivity scales linearly with the length of the sense fiber.

Fig. 2 shows a conventional IFOG in so-called minimum configuration. It consists of a (nearly) constant intensity broadband light source, an optical detector, a polarizer, two couplers, a phase modulator, and a fiber sense coil. In an IFOG, light from the source is divided by a 2x2 coupler and launched into the fiber sense coil in clockwise and counter-clockwise directions. The two counterpropagating light beams in the coil are combined by the same 2x2 coupler to form an interference fringe which is detected by the optical detector. The role of the phase modulator is to bias the interferometer at the quadrature point (maximum magnitude of slope of light output vs. applied voltage) and reduce receiver noise through synchronous detection. The polarizer ensures that only one single mode of the sensor is monitored (out of two polarization modes).

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Fig. 3 shows angle random walk (ARW), which is a measure of gyroscope noise, as a function of power received by the detector. The figure shows that RIN from the optical light source limits the lowest achievable ARW value. The flat part of the curve on the right side is

the region where RIN (independent of detected optical power P) overwhelms both the shot noise (shown as dashed $1/P^{1/2}$ dependence) and electronic (thermal) noise (shown as dashed $1/P$ dependence).

In order to improve IFOG performance, one needs to reduce optical RIN as shown in the following figure. Fig. 4 depicts ARW as a function of detector received power for 0, 10, 100x RIN reduction of an IFOG optical source. The plot predicts significant ARW improvements when RIN-reduced light is used. The price for lower ARW with RIN reduced sources is the requirement for higher received power at the detector. This requirement for increased detected power is still quite modest ($\sim$ mW), which makes the RIN reduction method a powerful tool for achieving low ARW, high performance IFOGs.

A low complexity means of optical RIN reduction for an IFOG broadband source is an in-line semiconductor optical amplifier (SOA) operating in the saturation regime, downstream of the source. Fig. 5 depicts an IFOG optical source, such as an erbium doped fiber amplifier (EDFA), input to a SOA operating in saturation. The saturated SOA provides a significant reduction in the RIN of the output light. A SOA in saturation behaves like a high pass filter for the amplitude of the light, as shown in Fig. 6. That is to say, the SOA will pass high frequency amplitude fluctuations of the light largely unchanged, but will damp out low frequency amplitude fluctuations. The characteristic frequencies for such a high pass filter are f_c and f_s , where f_c is related to semiconductor carrier lifetime (τ_c) and f_s is connected to the stimulated emission in the SOA as well as carrier lifetime ($\tau_s=1/f_s$). Carrier lifetime values are typically around 70 ps in semiconductors while τ_s is typically in the neighborhood of 700 ps, which places the rising high pass edge of SOA (maximum frequency of the most effective RIN suppression) slightly above 1 GHz. Since IFOGs generally operate at modulation frequencies at 1 MHz or below, the SOA effectively damps out the relevant amplitude fluctuations of the broadband source, with plenty of margin in the frequency response of the SOA. Therefore, following a broadband source (such as EDFA) with a saturated SOA is an effective means of reducing RIN for IFOG applications.

Figures 7a and 7b show block diagrams of laboratory measurement setups to measure RIN of an EDFA cascaded with one and two SOAs operating in deep saturation region. More details on RIN measurement techniques can be found in reference 6. Light from a commercial EDFA (MPB EFA-R35) is launched into one or two cascaded SOAs (Inphenix 1501 and 1502)) and RIN is analyzed using a high speed photodetector (Discovery

Semiconductor DSC50S) and an RF analyzer (Agilent N9000A). An RF amplifier (Miteq AM-1431) with high gain and low noise was used to boost the signal above RF spectrum analyzer noise floor. Fig. 8 shows cascaded EDFA-SOA (traces a and b) with each of the two SOAs, and EDFA-SOA-SOA (trace c) RIN measurement as a function of input optical power to both SOAs (the input power to each SOA is kept the same), with reference to EDFA RIN alone. Trace (a) shows RIN suppression as a function of input optical power into Inphenix 1502 SOA (2 mW saturated output power) while trace (b) depicts RIN suppression with the Inphenix 1501 SOA (10 mW saturated output power). Figs. 7a and 7b show 12 and 14 dB RIN suppression by injection of 10 mW into 1502 and 1501 Inphenix SOAs, respectively. Trace (c) illustrates RIN suppression of EDFA-SOA-SOA cascade which is even higher than individual SOA cases, namely 19.5 dB of RIN suppression with 10 dBm input power launched into both SOAs. The figure shows the effectiveness of the saturation regime, because to the far left of the plot, neither SOA is deep into saturation, but at the higher input powers to the right, the 1510 device is saturating and the 1502 device is deep into saturation, with much improved net RIN reduction. The measured RIN reduced optical output power from SOA was around 10 dBm. Such a RIN suppressed source can be used to achieve a significant lowering gyro noise as explained in the following.

In order to investigate the impact of the above RIN-reduced light source on IFOG performance, predicted ARW is calculated and plotted as a function of optical power received by the photodetector [7]. Fig. 9 shows two cases: (a) with non-RIN suppressed light and (b) with 19.4 dB RIN suppressed light. The IFOG parameters used in Fig. 9 are: 1 km fiber length, fiber coil diameter of 100 cm, operating wavelength 1550nm, and optical bandwidth of 30 nm, and detector noise-equivalent power (NEP) of $1 \text{ pW/Hz}^{1/2}$.

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As trace (a) in Fig. 9 shows, for an EDFA broadband source with no RIN reduction, IFOG ARW performance does not improve with optical power above 20 μW due to source RIN. However, ARW can be reduced by 12 dB by using the above EDFA-SOA-SOA 19.4 dB reduced source when 1 mW optical power is detected by photodiode (notional 10 dB loss is assumed for IFOG optical circuit). Greater noise improvements are possible if one is willing to deploy higher power sources and deliver more light on the IFOG photodiode. For example, delivery of 30 mW optical power on photodiode results in a predicted 18.0 dB reduction of

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gyro noise (as shown in Fig. 9) provided that the source power can be increased to 300 mW. Photodiodes capable of detecting 30 mW power without saturation are commercially available for 1.5 micron.

Following an optical source by one or more saturated SOAs as disclosed herein provides a compact, efficient, and low complexity RIN-suppressed optical source for the IFOG. The degree of RIN suppression (hence gyro noise reduction) is significant and is predicted to lead to as much as 20-30 dB gyro noise reduction. Such ultra-low-noise and compact IFOGs can be of navigation/strategic grade (1 milli-degree/root-hr) to even beyond strategic grade (10 micro-deg/root-hr) which have been the province of large mechanical or ring laser gyroscopes up to now.

Those of skill in the art will appreciate that incoherent broadband sources other than EFDAs may be used. Any wavelength band of light for which saturable amplifiers with fast gain dynamics can be fabricated can be used. Incoherent broadband light sources include superluminescent diodes (SLDs), other types of doped-fiber amplifiers, and semiconductor amplifiers.

Although SOAs are excellent choices for the present application, it is noted that other optical amplifiers with broad bandwidth, fast gain dynamics (greater than approximately 1MHz), capability of being operated in gain saturation, and with saturated output power of 10 microwatts or more, preferably milliwatts, can be used.

All of the references listed herein are incorporated into this patent application by reference in their entirety.

It is recognized that modifications and variations of the present invention will be apparent to those of ordinary skill in the art and it is intended that all such modifications and variations be included within the scope of the appended claims.

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- 5) Bennett, S.M. : "Apparatus and Method for Electronic RIN Reduction in Fiber-Optic
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- 6) Obarski, G.E. et al.: J. Opt. Soc. Am B-18(6), p.750, 2001
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What is claimed is:

- 1 1. Optical source comprising:
 - 2 a broadband, incoherent light source; and
 - 3 an optical amplifier in saturation arranged to receive light from the broadband,
 - 4 incoherent light source to generate output light having reduced relative intensity noise.
- 1 2. The optical source of claim 1 wherein the broadband, incoherent light source is an
- 2 erbium-doped fiber amplifier.
- 1 3. The optical source of claim 1 wherein the broadband incoherent light source is a
- 2 superluminescent diode.
- 1 4. The optical source of claim 1 wherein the optical amplifier is a semiconductor optical
- 2 amplifier.
- 1 5. The optical source of claim 1 wherein the optical amplifier has broad bandwidth, fast
- 2 gain dynamics, is operable in gain saturation, and has a saturated output power of at least
- 3 10 microwatts.
- 1 6. The optical source of claim 5 wherein the saturated output power is in the milliwatt
- 2 range.
- 1 7. Interferometric fiber optic gyroscope comprising:
 - 2 a broadband, incoherent light source;
 - 3 a semiconductor optical amplifier in saturation arranged to receive light from the
 - 4 broadband, incoherent light source to generate output light having reduced relative
 - 5 intensity noise;
 - 6 a fiber sense coil for receiving counter-propagating beams of the output light from the
 - 7 semiconductor optical amplifier; and
 - 8 an optical detector responsive to an interference fringe from which rotation rate is
 - 9 sensed.

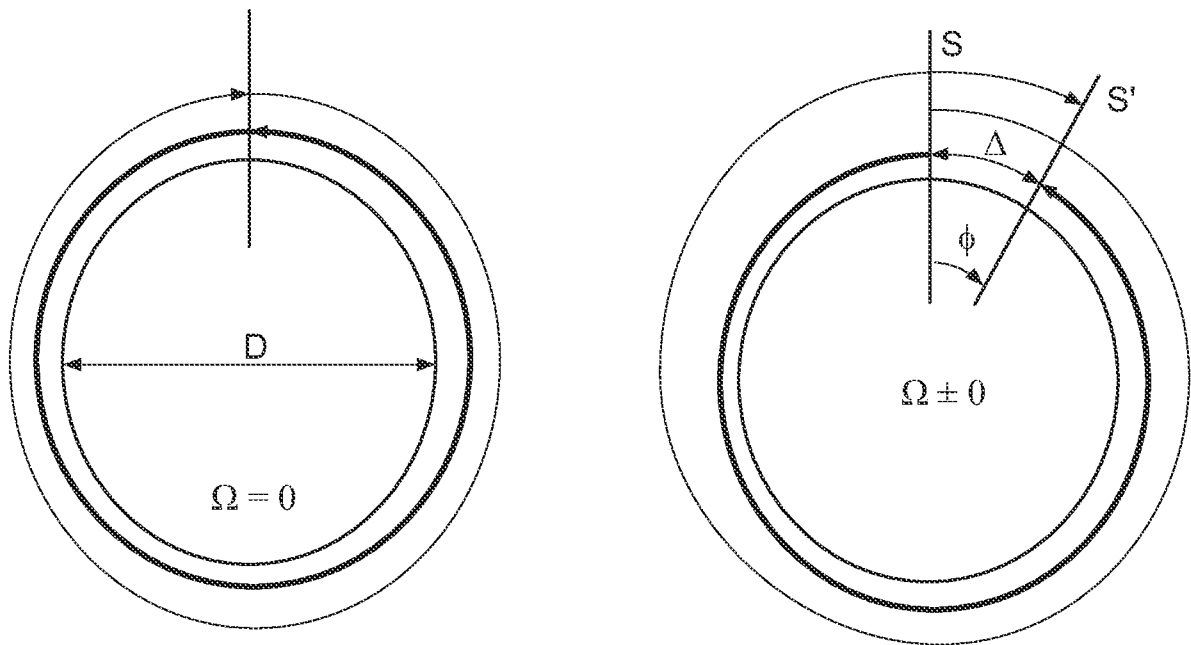
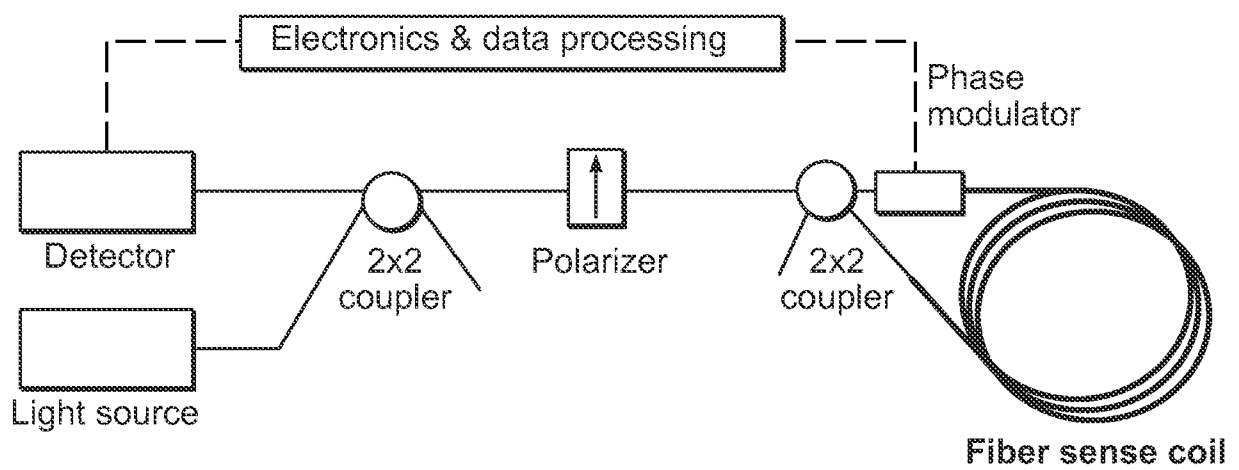


FIG. 1

PRIOR ART
FIG. 2

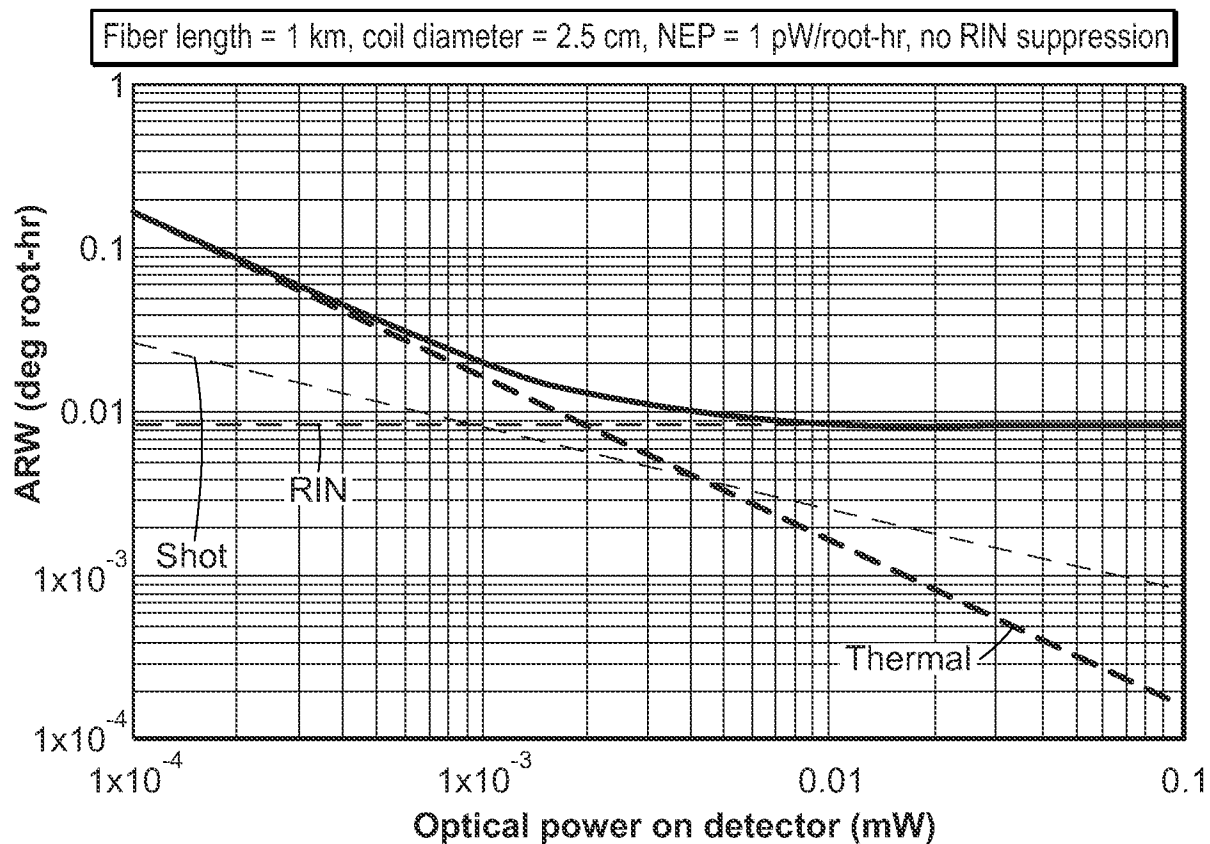


FIG. 3

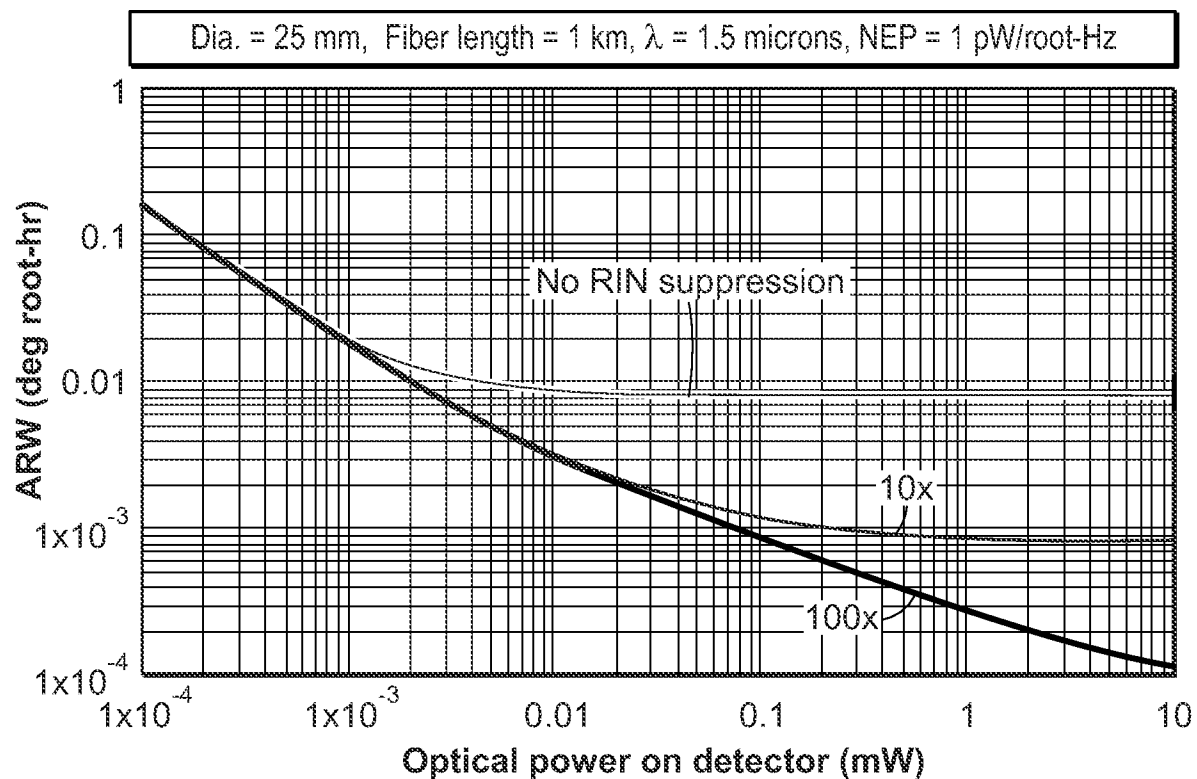


FIG. 4

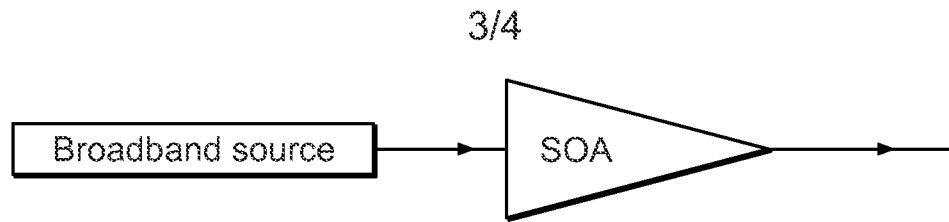


FIG. 5

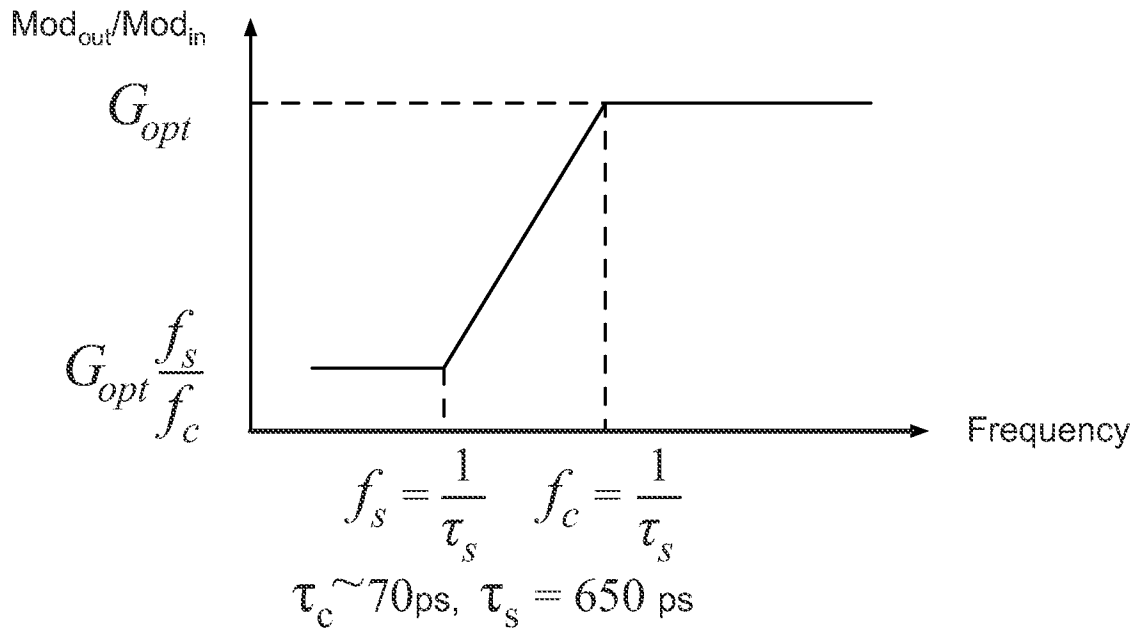


FIG. 6

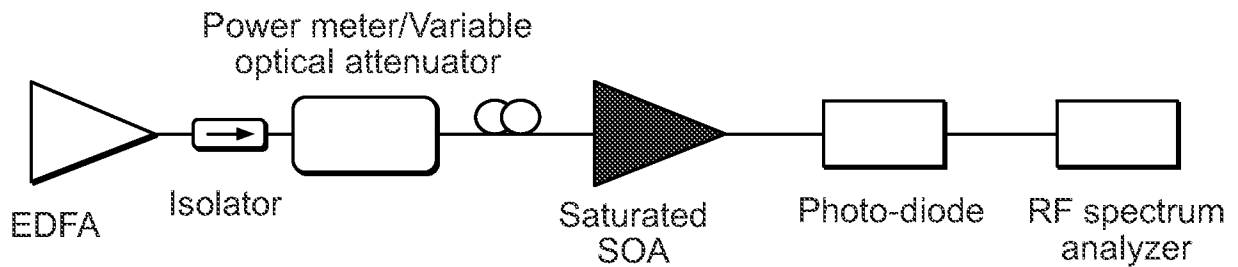


FIG. 7a

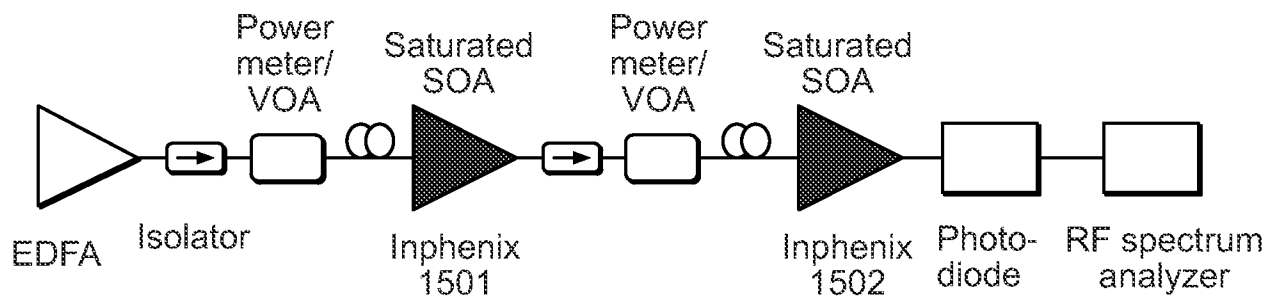


FIG. 7b

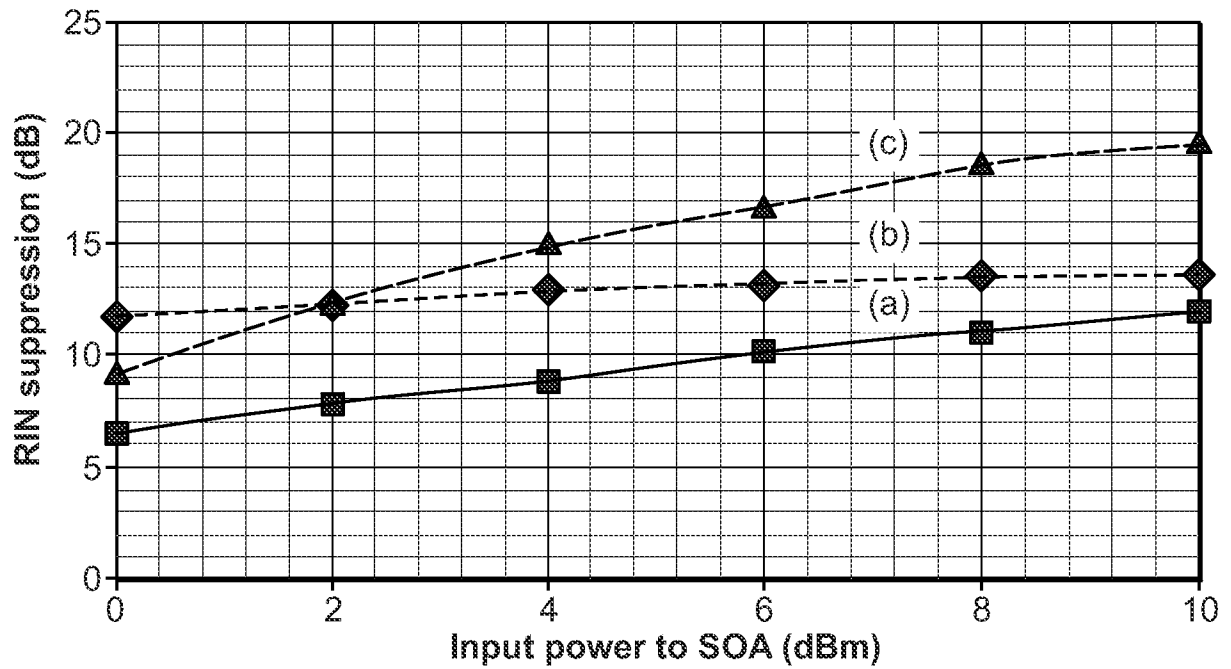


FIG. 8

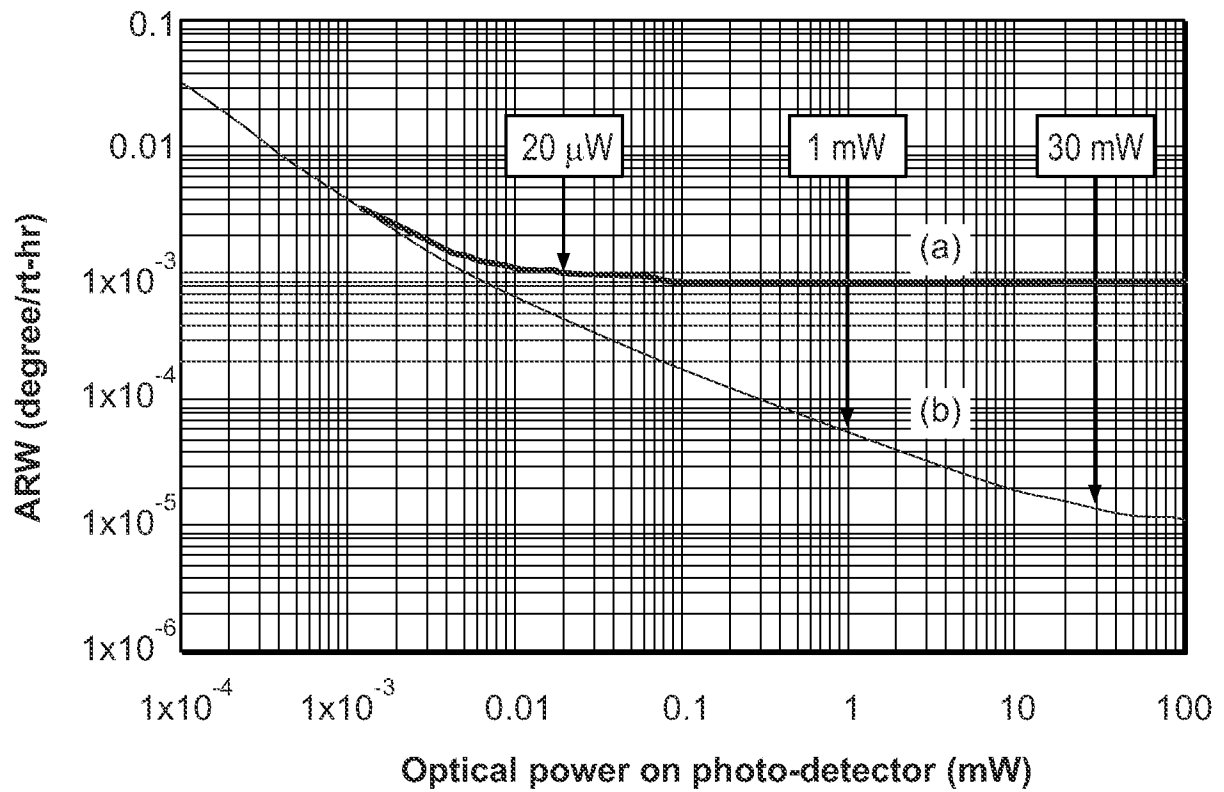


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 12/51034

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G01C 19/72 (2012.01)

USPC - 356/112

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): G01C 19/72

USPC: 356/112

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

IPC(8): G01 19/72 (keyword limited - see terms below)

USPC: 356/112; 356/350; 459-462 (keyword limited - see terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PUBWEST(PGPB, USPT, EPAB, JPAB), Patbase, Google Patents; Google Scholar; Search Terms: optical amplifier, broadband light source, diode, optical fiber, detector, gyroscope, noise reduction, coil, erbium

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,761,225 A (Fidric et al.) 2 June 1998 (02.06.1998) col 3, ln 56; col 3, ln 59; col 3, ln 58-60; col 4, ln 15-16; col 4, ln 24-25; col 5, ln 4-5; col 5, ln 9-12; col 6, ln 27; col 9, ln 8; col 9, ln 24-25; col 9, ln 27-29; col 9, ln 31; col 10, ln 36-37.	1-7
A	US 5,321,503 A (Bramson) 14 June 1994 (14.06.1994) entire document	1-7
A	US 5,781,296 A (Yamamoto et al.) 14 July 1998 (14.07.1998) entire document	1-7

☐ Further documents are listed in the continuation of Box C.

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