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(54) Title: OPTICAL FIBER CABLE FOR TRANSMISSION OF HIGH POWER LASER ENERGY OVER GREAT DISTANCES

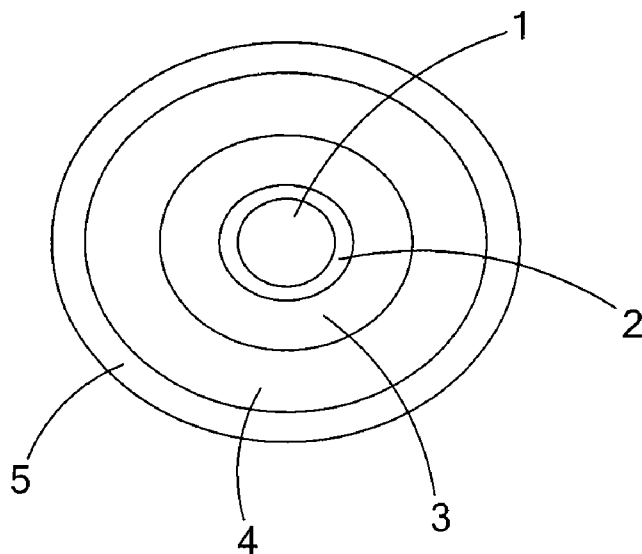


Fig. 1A

(57) Abstract: There is provided a system and apparatus for the transmission of high power laser energy over great distances without substantial power loss and without the presence of stimulated Raman scattering. There is further provided systems and optical fiber cable configurations and optical fiber structures for the delivering high power laser energy over great distances to a tool or surface to perform an operation or work with the tool or upon the surface.



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OPTICAL FIBER CABLE FOR TRANSMISSION OF HIGH POWER LASER ENERGY OVER GREAT DISTANCES

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[0001] This application is a continuation-in-part of U.S. Patent Application Serial number 12/544,136 filed August 19, 2009, title Method and Apparatus for Delivering High Power Laser Energy over Long Distances, which claims the benefit of the filing date of October 17, 2008 under 35 U.S.C. § 119(e)(1) of U.S. Provisional Application Serial Number 61/106,472, titled Transmission of High Optical Power Levels via Optical Fibers for Applications such as Rock Drilling and Power Transmission; and this application claims the benefit of priority under 35 U.S.C. § 119(e)(1) of the following listed applications: U.S. Provisional Application Serial Number 61/295,562, filed January 15, 2010, title Optical Fiber Cable for Transmission of High Power Laser Energy Over Great Distances and U.S. Provisional Application Serial number 61/153,271, filed February 17, 2009, title Method and Apparatus for an Armored High Power Optical Fiber for Providing Boreholes in the Earth; the entire disclosure of each of the above mentioned regular and provisional patent application are incorporated herein by reference.

[0002] This invention was made with Government support under Award DE-AR0000044 awarded by the Office of ARPA-E U.S. Department of Energy. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

25 Field of the Invention

[0003] The present invention relates to the construction and composition of optical fiber cables and laser systems utilizing such cables that provide for the ability to transmit high power laser energy over great distances, which distances and power transmission levels were heretofore believed to be unobtainable. The present invention further relates to the construction of such cables to withstand harsh environments. In particular, the present invention relates to a unique and novel combination of an optical fiber and a multi-layered structure for such cables.

[0004] As used herein, unless specified otherwise “high power laser energy” means a laser beam having at least about 5 kW (kilowatt) of power. As used herein, unless specified otherwise “great distances” means at least about 500 m (meter). As used herein the term “substantial loss of power” and “substantial power loss” means more than about 2.0 dB/km (decibel/kilometer) for a selected wavelength. As used herein the term “substantial power transmission” means at least about 50 % transmittance.

Discussion of Related Art

[0005] Until the present invention, it was believed that a paradigm existed in that the transmission of high power laser energy over great distances without substantial loss of power was unobtainable. As a consequence, it was further believed that there was no reason to construct, or investigate the composition of, an optical fiber or an optical fiber cable for the transmission of high power laser energy over great distances.

[0006] Power loss over long distances occurs in an optical fiber from many sources including: absorption loss, and in particular absorption loss from hydroxyl ions (OH⁻); Rayleigh scattering; Brillouin scattering; Raman scattering; defects; inclusions; and bending loss. These problems have been documented in the literature.

[0007] For example, in the 2006, Crystal Fiber White Paper, titled “Towards 100 kW fiber laser system Scaling up power in fiber lasers for beam combining” it is provided, at page 4, that for stimulated Brillouin scattering (SBS) “the threshold scales as the square of signal mode field diameter (MFD) and inversely with the effective fiber length. Hence, larger core size and short fiber length are desired for power scaling.” (emphasis original) In Corning paper, NIST-SOFM 2004, titled “Stimulated Brillouin Scattering: An Overview of Measurements, System Impairments, and Applications” it is provided, at page 1, that “[o]f the three types of scattering events [Rayleigh, Raman and Brillouin] stimulated Brillouin scattering (SBS) is recognized as the dominant optical fiber nonlinearity.” (bracketed matter added) The Corning paper, at page 3, goes on to provide that “[t]he output power curve . . . also shows that the signal power becomes depleted beyond a certain input power. This deleterious result will effectively clamp the signal output power, but continue to transfer power to the Stokes (reflected) signal via

the electrostrictive process which underlies the stimulated Brillouin phenomenon.”

Thus, the Corning paper, at page 4, provides that “[s]timulated Brillouin scattering is known to grossly limit the design of several optical transmission systems, amplifiers, and lasers.”

5 **[0008]** This perceived paradigm, expressed in the art to be believed to exist between length of fiber and power transmittance is further illustrated in the May 31, 2007, Vol. 5, Supplement, pages S39-S41, CHINESE OPTICS LETTERS, Muto et al., titled “Laser cutting for thick concrete by multi-pass technique”, although Muto states that 4 kW of power were delivered down a 1 km fiber, when 5 kW of laser power was
10 put into the fiber, Muto, however, fails to eliminate the stimulated Raman scattering SRS phenomena. As shown by Muto’s paper this deleterious phenomenon will effectively clamp the output power as length or power is increased. The SRS phenomenon is seen by the spectrum that is shown in figure 3 of Muto, which figure is provided herein as FIG. 2 in this specification. In FIG. 2 the laser beam is shown as band 200 and the
15 SRS is shown as band 201. Thus, prior to the present invention, it was believed that as input laser power, or the length of the fiber increased, the power output of a fiber would not increase because of the SBS, SRS and other nonlinear phenomenon. In particular, SBS would transfer the output power to back up the fiber toward the input. Further, SBS, SRS, as well as the other deleterious nonlinear effects, in addition to limiting the
20 amount of power that can be transmitted out of the fiber, can result in fiber heating and ultimate failure. Thus, as recognized by Muto, at page S41 “[i]t is found that 10-kW power delivery is feasible through a 250-m-long fiber with the core diameter of 150 μ m. The physical phenomenon which restricts the transmitted power is SRS.” Thus, Muto, as did others before him, failed to deliver high power laser energy over great distances.

25 **[0009]** The present invention breaks this length-power-paradigm, and advances the art of high power laser delivery beyond this paradigm, by providing an optical fiber cable laser system that overcomes these and other losses, brought about by nonlinear effects, and provides for the transmission of high power laser energy over great distances without substantial power loss.

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SUMMARY

[0010] It is desirable to have an optical fiber cable that provides for the delivery of high power laser energy over great distances and without substantial power loss. The present invention, among other things, solves this need by providing the articles taught herein.

[0011] Thus there is provided herein an optical fiber cable for transmitting high power laser energy over great distances, the cable can have a length that is greater than about 0.5 km, greater than 2 km greater than about 3 km or greater than about 5 km; the cable is a layered structure comprising: a core; a cladding; a coating; a first protective layer; and, a second protective layer, the cable is capable of transmitting laser energy having a power greater than or equal to about 1 kW, about 5 kW or about 10 kW, over the length of the cable with a power loss of less than about 2 dB/km and preferably less than about 1 dB/km and more preferably less than about 0.3 dB/km for a selected wavelength. There is further provided such an optical fiber cable that delivers the laser energy to a tool or surface having a spectrum that is substantially free from SRS phenomena.

[0012] A system for delivering high power laser energy to a tool, the system having a high power laser having a power of at least about 1 kW, at least about 5 kW or at least about 10 kW. The system having an optical fiber cable having a core; cladding; coating; and, a first protective layer. The system having a tool. The cable in the system having first and second ends and a length between the first and second end; the length of the cable being greater than 0.5 km, greater than about 1 km, greater than about 2 km, or greater than about 3 km. The first end of the cable being optically associated or connected to the laser and the second end of the cable being associated with and preferably optically associated with or connected to the tool. The laser beam, from at least in part the laser, transmitted in the cable and having a power of at least about 1 kW at the first end of the cable, and, the power loss of the laser beam in the cable from the first end to the second end being less than about 2 dB/km and preferably being less than about 1 dB/km and more preferably less than about 0.5 dB/km for a selected wavelength. There is further provided such an optical fiber cable that delivers the laser

energy to a tool or surface having a spectrum in which the SRS phenomena is substantially absent.

5 **[0013]** A spool of optical fiber cable for transmitting laser energy over great distances. The spool having a cable wound around the spool, the cable being capable of being unwound from and wound onto the spool, and thus being rewindable. The cable having a length greater than about 0.5 km, about 1 km, about 2 km or about 3 km and comprising: a core; a cladding; a coating; a first protective layer; and, a second protective layer. The cable is capable of transmitting high power laser energy for its length with a power loss of less than about 2 dB/km and more preferably less than 10 about 1 dB/km and still more preferably less than about 0.5 dB/km and yet more preferably about 0.3 dB/km. The outer diameter of the spool when wound is less than about 6 m to facilitate transporting of the cable by truck. .

BRIEF DESCRIPTION OF THE DRAWINGS

15 **[0014]** FIG. 1A is a transverse cross sectional view, not necessarily to scale, showing the structure of an optical fiber cable of the present invention.

[0015] FIG. 1B is a longitudinal cross sectional view of the optical fiber cable of FIG. 1A.

20 **[0016]** FIG. 2 is a prior art spectrum showing the presence of SRS phenomena.

[0017] FIG. 3 is a schematic of a testing system.

[0018] FIGS. 4-6 are spectrums of laser energy transmitted by the present invention showing the absence of SRS phenomena.

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DESCRIPTION OF THE DRAWINGS AND THE PREFERRED EMBODIMENTS

30 **[0019]** In general, the present inventions relate to optical fiber structures for transmitting high power laser energy over great distances without substantial loss of

power. This invention further relates to the structure of optical fiber cables and, without limitation, the structure of such cables for use in harsh environments.

[0020] Thus, in general there is provided in Figs. 1A and 1B an optical fiber cable having a core 1, a cladding 2, a coating 3, a first protective layer 4, and a second protective layer 5. Although shown in the figures as being concentric, it is understood that the components may be located off-center, off-center and on-center at different locations, and that the core, the core and cladding and the core, cladding and coating maybe longer or shorter than the one or more of the protective layers.

[0021] The core 1 is preferably composed of fused silica having a water content of at most about 0.25 ppm. The core may be composed of other materials, such as those disclosed in patent application serial number 12/544,136, the entire disclosure of which is incorporated herein by reference. Higher purity materials, and the highest purity material available, for use in the core are preferred. Thus this higher purity material minimizes the scattering losses caused by defects and inclusions. The core is about 200 to about 700 microns in diameter, preferably from about 500 to about 600 microns in diameter and more preferably about 600 microns in diameter. As used herein the term "about" would include ranges of plus or minus 10%.

[0022] The cladding 2 is preferably composed of fluorine doped fused silica. The cladding may be composed of other materials such as fused silica doped with index-altering ions (germanium), as well as those disclosed in patent application serial number 12/544,136, the disclosure of which is incorporated herein by reference. The cladding thickness, depending upon the wavelength being used and the core diameter, is from about 50 microns to about 250 microns, preferably about 40 microns to about 70 microns and more preferably about 60 microns. As used herein with respect to a multi-layer structure, the term "thickness" means the distance between the layer's inner diameter and its outer diameter. The thickness of the cladding is dependent upon and relative to the core size and the intended wavelength. In general for 1.1 micron wavelength the outer diameter of the cladding should be 1.1 x the outer diameter of core or greater; and, for a 1.5 micron wavelength the outer diameter of the cladding should be 1.5 x the outer diameter of the core or greater. Although a single cladding is illustrated, it is understood that multiple cladding may be utilized.

[0023] The coating 3 is preferably composed of a high temperature acrylate polymer, for higher temperatures a polyimide coating is desirable. The coating may be composed of other materials, such a metal, as well as those disclosed in patent application serial number 12/544,136, the disclosures of which are incorporated herein
5 by reference. The coating thickness is preferably from about 50 microns to about 250 microns, preferably about 40 microns to about 150 microns and more preferably about 90 microns. The coating thickness may even be thicker for extreme environments, conditions and special uses or it may be thinner for environments and uses that are less demanding. It can be tailored to protect against specific environmental and/or physical
10 risks to the core and cladding that may be encountered and/or anticipated in a specific use for the cable.

[0024] The first protective layer 4 and the second protective layer 5 may be the same or they may be different, or they may be a single composite layer comprising different materials. Preferably the first and second protective layers are different
15 materials.

[0025] The first protective layer is preferably thixotropic gel. In this preferred embodiment, this layer primarily protects the fiber from absorption loss from hydroxyl ions and vibration. The thixotropic gel protects the fiber from mechanical damage due to vibrations, as well as, provides support for the fiber when hanging
20 vertically because its viscosity increases when it is static. A palladium additive is be added to the thixotropic gel to provide hydrogen scavenging. The hydrogen which diffuses into the fiber may be problematic for Germanium or similar ion doped cores. When using a pure silica doped core, it is less of an effect. The first protective layer may be composed of other materials, such as those disclosed in patent
25 application serial number 12/544,136, the entire disclosure of which is incorporated herein by reference. The thickness of the first protective layer should be selected based upon the environment and conditions of use as well as the desired flexibility and/or stiffness of the cable. Thus, the composition and thickness of the first protective layer can be tailored to protect against specific environmental and/or physical risks to the
30 core, cladding and coating that may be encountered and/or anticipated in a specific use for the cable. Thus, the use of the preferred thixotropic gel provides the dual benefit of

adding in the manufacture of the cable as well as providing mechanical protection to the core once the cable manufacturing is completed.

[0026] The second protective layer is preferably a stainless steel tube composed of 316 stainless. The second protective layer preferably provides physical strength to the fiber over great distances, as well as, protection from physical damage and the environment in which the cable may be used. The second protective layer may be composed of other materials, such as those disclosed in patent application serial number 12/544,136, the entire disclosure of which is incorporated herein by reference. The second protective layer thickness should be selected based upon the requirements for use and the environment in which the cable will be used. The thickness may further be dependent upon the weight and strength of the material from which it is made. Thus, the thickness and composition of the second protective layer can be tailored to protect against specific environmental and/or physical risks to the core, cladding and coating that may be encountered and/or anticipated in a specific use for the cable.

[0027] The optical fiber cables can be greater than about 0.5 km (kilometer), greater than about 1 km, greater than about 2 km, greater than about 3 km, greater than about 4 km and greater than about 5 km. The preferred fibers using the preferred first and second protective layers can withstand temperatures of up to about 300 degrees C, pressures of up to about 3000 psi and as great as 36,000 psi, and corrosive environments over the length of the fiber without substantial loss of power and for extended periods of time. The optical fiber cables can have a power loss, for a given wavelength, of less than about 2.0 dB/km, less than about 1.5 dB/km, less than about 1.0 dB/km, less than about 0.5 dB/km and less than about 0.3 dB/km. The optical fiber cables can have power transmissions of at least about 50%, at least about 60%, at least about 80%, and at least about 90%.

[0028] The flexibility and/or stiffness of the cable can be varied based upon the size and types of materials that are used in the various layers of the cable. Thus, depending upon the application a stiffer or more flexible cable may be desirable. It is preferred that the cables have sufficient flexibility and strength to be capable of being repeatedly wound and unwound from a spool or reel having an outside diameter of no more than about 6 meters. This outside diameter spool size can be transported by truck

on public highways. Thus, the present invention encompasses a spool or reel having an outside diameter of less than about 6 meters and comprising between 0.5 meters and 5 km of the optical fiber cable of the present invention; a spool or reel having an outside diameter of less than about 6 meters and comprising greater than about 0.5 km (kilometer), greater than about 1 km, greater than about 2 km, greater than about 3 km, greater than about 4 km and greater than about 5 km in length of the optical fiber cable of the present invention.

[0029] Any type of high power laser may be used as a source of laser energy for use with the optical fiber cables of the present invention. Examples of such lasers are disclosed in patent application serial number 12/544,136, the disclosures of which are incorporated herein by reference. The composition and construction of the optical fiber cable, and in particular the composition of the core and cladding, should be selected to optimize the reduction in power loss for the particular beam that the laser generates. It is believed that lasers that generate a beam having a wavelength of about 800 nm to about 2000 nm, may see acceptable power loss, *i.e.*, have a benefit, when used with the cables of the present invention. However, wavelengths from about 1060 nm to about 1100 nm and about 1470 nm to about 1600 nm have a greater potential benefit. High power infrared lasers are preferable. At present wavelengths of about 1490 nm, about 1550 nm, and about 1080 nm have even greater potential benefits and are preferred. Further, broad band beams within these wavelength ranges may have greater benefits. Preferably, the laser should generate a laser beam in the infrared wavelength having a power of at least about 1 kW, at least about 3 kW, at least about 5 kW, at least about 10 kW, and at least about 20 kW or greater.

[0030] An example of such a preferred laser for use with the optical fiber cables of the present invention is the IPG 20000 YB. The detailed properties of this laser are disclosed in patent application serial number 12/544,136, the disclosures of which are incorporated herein by reference. The preferred laser consists of 20 modules. The gain bandwidth of a fiber laser is on the order of 20 nm, the linewidth of the free oscillator is 3 nm, Full Width Half Maximum (FWHM) and may range from 3 nm to 5 nm (although higher linewidths including 10 nm are envisioned and contemplated). Each module's wavelength is slightly different. The modules further each create a multi-

mode beam. Thus, the cumulative effect of combining the beams from the modules is to maintain the Raman gain and the Brillouin gain at a lower value corresponding to the wavelengths and linewidths of the individual modules, and thus, consequently reducing the SBS and SRS phenomenon in the fiber when the combined beams are transmitted through the fiber.

[0031] The testing system of FIG. 3 can be used to evaluate various fibers of the present invention. Thus, there is provided a laser 301, a short, less than about 25 m, 300 μ m fiber 302 connecting the laser to a QBH connector 303, which connects the fiber 302 to a collimator 304. The collimator 304 collimates the laser beam and passes the beam through a ¼% beam sampler 305. The beam may be directed at this point in the system to ¼% beam sampler 306, a beam dump 307, or collimator 308. Collimator 308 focuses the beam to input the beam into QBH connector 309. Collimator 308 comprises a focusing lens, a heat sink, and a fiber receptacle. Connector 309 is connected to collimator 308. Connector 309 is affixed to the long test fiber 310. The long test fiber 310 has a QBH connector 311, which connects long test the fiber 310 to a collimator 312. The laser beam travels from collimator 312 to ¼% beam sampler 313. From sampler 313 the beam can travel to a power meter 314 or an optical spectrum analyzer (OSA) 315. Optical time domain reflectometer (OTDR) 316, transmits and receives a timed laser beam through sampler 316, to sampler 305 and then along fiber 310. The OTDR 315 may also be used to test the fiber 310 separate from the laser 301. The laser beam from laser 301 travels from sampler 306 to ¼% beam sampler 317 and then to either OSA 315 or to power meter 318.

[0032] EXAMPLE 1

[0033] An example of an embodiment of the optical fiber cable of the present invention is a fused silica core of about 600 microns diameter, a fluorine doped fused silica cladding, having a thickness of 60 microns, a high temperature Acrylate coating having a thickness of about 90 microns, a thixotropic gel first protective layer having a thickness of about 2500 microns, and a 316 stainless steel second protective layer having an outer diameter of about 6250 microns and a length of about 2 km. The length of the fiber structure comprising the core, cladding and coating is longer than the length of the stainless steel protective layer. This difference in length addresses any

differential stretch of the stainless steel relative to the stretch of the fiber structure when the cable is in a hanging position, or under tensions, such as when it is extended down a well bore. The fiber has a numerical aperture of at least about 0.14. The fiber of this example can transmit a laser beam (wavelength 1080 nm) of about 20 kW (kilowatt) power, from the preferred laser, over a distance of about 2 km in temperatures of up to about 200 degrees C and pressures of about 3000 psi with less than 1 dB/km power loss.

[0034] EXAMPLE 2

An example of an embodiment of the optical fiber cable of the present invention would have a fused silica core of about 500 microns diameter, a fluorine doped fused silica cladding, having a thickness of 50 microns, an Acrylate coating having a thickness of about 60 microns, and an 1/8 inch outer diameter stainless steel protective layer and a length of about 2 km. The fiber has a numerical aperture (NA) of 0.22. The fiber of this example transmitted a laser beam (wavelength 1080 nm) of about 10 kW (kilowatt) power, from the preferred laser, over a distance of about 2 km in temperatures of up to about 150 degrees C and at ambient pressure and with less than 0.8 dB/km power loss.

[0036] EXAMPLE 3

An example of an embodiment of the optical fiber cable of the present invention is a fused silica core of about 600 microns diameter, a fluorine doped fused silica cladding, having a thickness of 60 microns, a high temperature Acrylate coating having a thickness of about 90 microns, and a 1/8 inch outer diameter stainless steel protective layer and a length of about 0.5 km. The fiber had a numerical aperture of 0.17. The fiber of this example transmitted a laser beam (wavelength 1080 nm) of about 10 kW power from the preferred laser, over a distance of about 0.5 km in temperatures of up to about 200 degrees C and at ambient pressure and with less than 1 dB/km power loss.

[0038] EXAMPLE 4

The preferred IPG 20000 YB laser was operated a duty cycle of 10% for a 1 kHz pulse rate. The operating conditions for this example were established to keep the pulse duration longer than the time constant for SBS. Thus, the absence of

SBS was the result of the fiber and laser, not the pulse duration. The laser beam was transmitted through the 2 km fiber of Example 2, evaluated in a test system along the lines of the test system shown in FIG. 3 and provided the results set forth in Table I, where peak power launched and power output are in watts.

5 **[0040] Table I.**

Peak Power Launched	Peak Power Output	Percentage transmitted
924	452	48.9
1535	864	56.3
1563	844	54.0
1660	864	52.0
1818	970	53.3
1932	1045	54.1
2000	1100	55.0
2224	1153	51.8
2297	1216	52.9
2495	1250	50.1
2632	1329	50.5
2756	1421	51.6
3028	1592	52.6
3421	1816	53.1
3684	1987	53.9
3947	2105	53.3
4342	2263	52.1
4605	2382	51.7
4868	2487	51.1

[0041] The spectrum for 4868 Watt power is shown at FIG. 4. The absence of SRS phenomenon is clearly shown in the spectrum. (As used herein terms such as, "absence of", "without any" or "free from" a particular phenomena or effect means that for all practical purpose the phenomena or effect is not present, and/or not observable by ordinary means used by one of skill in the art) Further the linear relationship of the launch (input) and output power confirms the absence of SBS phenomena. Further, the pulsed operation of the laser may have caused the wavelength of the fiber laser to chirp, which may have further contributed to the suppression of SBS and SRS phenomenon since this would result in an effectively wider laser linewidth.

15 **[0042] EXAMPLE 5**

[0043] The preferred IPG 20000 YB laser was operated to provide a continuous wave. As set forth below in the table 1, 2, 4 and 6 modules were used. For each power the laser was fired for about 2 minutes and 15 seconds. The laser beam was transmitted through the 2 km fiber of Example 2, evaluated in a test system along the lines of the test system shown in FIG. 3 and provided the results set forth in Tables II, where laser power (input power), and power output are in watts and power throughput is synonymous with transmittance.

[0044] Table II.

One Module	Laser Setting	Laser Power	Output of 2km Fiber	Power Throughput
	%	Watts	Watts	
	10	25	20	80%
	11	70	52	74%
	12	80	59	74%
	13	90	66.5	74%
	14	90	73.9	82%
	15	110	81.5	74%
	16	120	89.2	74%
	17	130	96.5	74%
	18	140	104.2	74%
	19	150	111.2	74%
	20	160	118.8	74%
	21	170	126.2	74%
	22	180	133.2	74%
	23	190	140.5	74%
	24	200	147.9	74%
	25	210	155.2	74%
	26	220	160.4	73%
	27	230	167.2	73%
	28	240	181	75%
	29	260	177.7	68%
	31	280	191.8	69%
	33	300	206.7	69%
	35	330	221.5	67%
	37	350	236.4	68%
	39	360	250.1	69%
	41	390	263.3	68%
One Module				
	23	190	120	63%
	35	330	215	65%

	41	400	257	64%
	45	430	288	67%
	50	490	313	64%
	55	540	352	65%
	60	590	382	65%
	65	640	411	64%
	70	690	477	69%
	75	750	493	66%
	80	800	525	66%
	85	850	565	66%
	90	900	599	67%
	95	950	625	66%
	100	1000	647	65%
Two modules				
	50	990	655	66%
	55	1100	709	64%
	60	1200	820	68%
	65	1310	855	65%
	70	1410	940	67%
	75	1510	1005	67%
	80	1620	1060	65%
	85	1730	1200	69%
	90	1830	1220	67%
	95	1930	1265	66%
	100	2000	1340	67%
Four Modules				
	50	1999	1310	66%
	55	2200	1460	66%
	60	2410	1588	66%
	65	2630	1740	66%
	70	2800	1852	66%
	75	3040	2000	66%
	80	3250	2130	66%
	85	3460	2290	66%
	90	3670	2430	66%
	95	3870	2535	66%
	100	4000	2675	67%
Six Modules				
	65	4040	2665	66%
	70	4350	2875	66%
	75	4650	3100	67%

	80	4930	3300	67%
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[0045] The spectrum for 4 modules at 100% laser setting is shown at FIG. 5. The absence of SRS phenomenon is clearly shown in the spectrum. Further the linear relationship of the input and output power confirms the absence of SBS phenomena.

[0046] EXAMPLE 6

5 **[0047]** The preferred IPG 20000 YB laser was operated to provide a continuous wave. One module was used. For each power the laser was fired for about 2 minutes and 15 seconds. The laser beam was transmitted through the 0.5 km fiber of Example 3, evaluated in a test system along the lines of the test system shown in FIG. 3 and provided the results set forth in Tables III and IV, where laser power (input power),
10 and power output are in watts and power throughput is synonymous with transmittance.

[0048] Table III.

Power in (W)	Power out (W)	% Transmission
220	196	89.09%
440	380	86.36%
660	560	84.85%
880	740	84.09%
1000	840	84.00%
1000	860	86.00%
1000	880	88.00%
1000	850	85.00%
1000	850	85.00%
1000	850	85.00%
1000	850	85.00%

[0049] Table IV.

Number of Modules	% laser power	Power in (W)	Power out (W)	% Transmission
1	30	270	253	93.70%
1	30	270	244	90.37%
1	35	320	300	93.75%
1	40	390	370	94.87%
1	45	430	390	90.70%
1	30	270	247	91.48%
5	15	580	520	89.66%
5	20	860	770	89.53%
5	25	1140	980	85.96%
5	30	1420	1230	86.62%

5	35	1700	1440	84.71%
5	40	1970	1700	86.29%
5	45	2250	1910	84.89%
5	50	2520	2150	85.32%
5	55	2790	2350	84.23%
5	60	3060	2600	84.97%
5	65	3320	2800	84.34%
5	70	3590	3000	83.57%
5	75	3850	3200	83.12%
5	80	4120	3500	84.95%

[0050] EXAMPLE 7

[0051] The preferred IPG 20000 YB laser was operated to provide a continuous wave. As set forth below in the table, 2, 6, 8 and 10 modules were used.

For each power the laser was fired for about 2 minutes and 15 seconds. The laser beam was transmitted through the 2 km fiber of Example 2, evaluated in a test system along the lines of the test system shown in FIG. 3 and provided the results set forth in Table V, where laser power (input power), and power output are in watts and power throughput is synonymous with transmittance.

[0052] Table V.

Modules	Laser Setting	Laser Power	Output of 2k Fiber	Throughput
	%	Watts	Watts	
Two Modules				
	10	50	39	78%
	15	220	162	74%
	20	330	243	74%
	25	440	320	73%
	30	550	420	76%
	35	660	470	71%
	40	770	550	71%
	45	880	650	74%
	50	990	700	71%
	55	1100	770	70%
	60	1200	850	71%
	65	1310	940	72%
	70	1420	990	70%
	75	1510	1070	71%
	80	1610	1130	70%
	85	1720	1200	70%
	90	1820	1290	71%
	95	1930	1370	71%

	100	2020	1420	70%
Six Modules				
	10	150	130	87%
	20	1040	710	68%
	25	1380	940	68%
	30	1720	1200	70%
	35	2050	1420	69%
	40	2390	1660	69%
	45	2720	1900	70%
	50	3050	2140	70%
	55	3390	2350	69%
	60	3710	2580	70%
	65	4030	2810	70%
	70	4350	3100	71%
	75	4660	3200	69%
	80	4980	3500	70%
	85	5300	3700	70%
	90	5620	3900	69%
	95	5910	4100	69%
	100	6210	4300	69%
Eight Modules				
	40	3200	2150	67%
	45	3650	2400	66%
	50	4090	2750	67%
	55	4530	3100	68%
	60	4970	3400	68%
	65	5390	3700	69%
	70	5820	4000	69%
	75	6240	4300	69%
	80	6650	4600	69%
	85	7080	4900	69%
	90	7500	5200	69%
	95	7920	5400	68%
	100	8280	5700	69%
Ten Modules				
	10	280	202	72%
	15	1190	860	72%
	20	1750	1210	69%
	25	2320	1610	69%
	30	2880	1980	69%
	35	3440	2380	69%
	40	4000	2750	69%
	45	4550	3100	68%

	50	5100	3500	69%
	55	5640	3900	69%
	60	6170	4300	70%
	65	6690	4600	69%
	70	7220	5000	69%
	75	7740	5300	68%
	80	8270	5700	69%
	85	8790	6000	68%
	90	9300	6300	68%

[0053] The spectrum for 10 modules at 9300 W output power, 90% laser setting is shown at FIG. 6. The absence of SRS phenomenon is clearly shown in the spectrum. Further the linear relationship of the input and output power confirms the absence of SBS phenomena.

5 **[0054]** The optical fiber cables of the present invention will have many and varied uses, some of which have yet to be realized. Thus, the optical fiber cables may be used to provide laser energy for use in well known laser tools, such as laser welding and cutting tools. It may be used to provide laser energy for use in newly developed and innovative laser tools, such as laser bottom hole assemblies for advancing
10 boreholes, *e.g.*, patent applications serial number 61/247,796 filed October 1, 2009 title Method of Communicating Power and/or Data Through a Mud Motor and serial number 12/544,038 filed August 19, 2009, titled Apparatus for Advancing a Wellbore using High Power Laser Energy. It may be used to provide laser energy for use in the construction of pipelines. Further, the optical fiber cables of the present invention, because of their
15 ability to be constructed of lightweight high strength material and to provide high power over great distances, maybe used to convert and/or create laser mechanical tools and equipment such as tunneling and earth boring and removal machines. Yet further, the cables of the present invention, because of their ability to be constructed of light weight high strength material and to provide high power over great distances, have the
20 capability of being used in any application known or later discovered where the efficient transmission of high power energy over great distances is needed, useful and/or beneficial.

[0055] The optical fiber cables of the present invention may further be incorporated into, contained in, or used in conjunction with other tubular and/or wire

types of equipments, such as for example, coiled tubing used in the drilling industry, drill pipe used in the drilling industry, and cables used for lowering, raising, holding and connecting equipment. The optical fiber cables of the present invention may be bundled together for a particular application, thus a plurality of cables may be used in a particular application and may be incorporated into, or enclosed within, and/or associated with tubulars, such as coiled tubing, drill pipe, casing and riser used in the drilling industry. Moreover, the optical fiber cables may be connected to each other. Further, a single cable may be connect to, or branched into using switches, several cables. In this way one high power laser may be used to provide high power energy to multiple tools over great distances and/or to provide high power laser energy to multiple tools that are separated by great distances.

[0056] Further although the use of single length of fiber, i.e., the length of fiber is made up of one fiber rather than a series of fibers coupled, spliced or other wise optically affixed end to end, for the longer distance power transmission is preferred, the use of multiple lengths of fiber joined end to end may be utilized. Moreover, several lengths of the optical fiber cables, or several lengths of fiber core structures, or combinations of both, many be joined into a plurality of such structures, such as in a bundle of optical fiber cables, fiber core structures or combinations of both.

[0057] Thus, the optical fiber cables of the present invention may be used to deliver high power laser energy over great distances to tools or machines, such as welders, cutters, earth boring, earth removal, and material removal equipment, in which the laser energy is then directed by such tools or machines onto a surface, material or work piece. Further, the optical fibers of the present invention may be used to provide operational power, e.g., power to operate a machine or device, over great distances.

The optical fibers cables of the present invention can provide high power laser energy over great distances, for such uses, in harsh environments, such as for example in mines, tunnels, boreholes, shipyards, factories, nuclear sites, elevated temperatures, caustic conditions, corrosive conditions, and under water.

[0058] From the foregoing description, one skilled in the art can readily ascertain the essential characteristics of this invention, and without departing from the

spirit and scope thereof, can make various changes and/or modifications of the invention to adapt it to various usages and conditions.

What is claimed:

1. An optical fiber cable for transmitting high power laser energy over great
5 distances comprising: an optical fiber cable having a length that is greater than about 0.5 km; the cable comprising: a core; a cladding; a coating; a first protective layer; and, a second protective layer; wherein, the cable is capable of transmitting laser energy having a power greater than or equal to about 5 kW over the length of the cable with a power loss of less than about 2 dB/km and without the presence of a stimulated Raman
10 scattering spectral band.
2. The cable of claim 1, having a length greater than about 1 km.
3. The cable of claim 1, having a length greater than about 2 km.
4. The cable of claim 1, having a length greater than about 3 km.
5. The cable of claim 1, having a length greater than about 1 km; and wherein the
15 power is greater than about 10 kW.
6. The cable of claim 5, having a length greater than about 2 km.
7. The cable of claim 5, having a length greater than about 3 km.
8. The cable of claim 1, wherein the second protective layer is longer than the core.
9. The cable of claim 1, wherein the core has a diameter of at least about 500
20 microns.
10. An optical fiber cable for transmitting high power laser energy over great distances comprising:
 - a. a cable having an input end for receiving laser energy and an output end of delivering laser energy to a tool or surface;
 - 25 b. the cable having a length between the input end and the output end that is at least about 1 km;
 - c. the cable comprising: a core and a means for protection;

- d. the core having a diameter of at least about 500 microns;
 - e. the cable input end configured to receive high power laser energy from a laser having a power greater than or equal to about 5 kW; and,
 - f. the cable output end configured to deliver at least about 70% of the received laser energy.
- 5
- 11. The cable of claim 10, wherein the length is at least about 2 km.
 - 12. The cable of claim 10, wherein the core is longer than the means for protection.
 - 13. The cable of claim 10, where the delivered laser energy has a spectrum that is substantially free from stimulated Raman scattering.
- 10
- 14. An optical fiber cable for transmitting high power laser energy over great distances: the cable having a length that is at least about 1 km; the cable comprising: a fiber core and an outer protective layer; wherein, the cable is capable of transmitting laser energy having a power greater than or equal to about 5 kW over the length of the cable with a power transmission of at least about 60% and without the presence of a
- 15
- stimulated Raman scattering spectral band.
- 15. A system for delivering high power laser energy to a tool, the system comprising:
 - a. a high power laser having a power of at least about 1 kW;
 - b. an optical fiber cable comprising:
 - i. a core;
 - 20 ii. a cladding;
 - iii. a coating; and,
 - iv. a protective layer;
 - c. a tool;
 - d. the cable having a first and second end and a length between the first and
- 25
- second end;
 - e. the length of the cable being greater than 2 km;

- f. the first end of the cable optically associated with the laser and the second end of the cable optically associated with the tool;
 - g. a laser beam transmitted in the cable and having a power of at least about 1 kW at the first end of the cable; and,
 - 5 h. the power loss of the laser beam in the cable from the first end to the second end being less than about 2 dB/km.
- 16. The system of claim 15, wherein the laser beam power at the first end is greater than or equal to about 5 kW.
- 17. The system of claim 15, wherein the laser beam power at the first end is greater
10 than or equal to about 10 kW.
- 18. The system of claim 15, wherein the power loss is less than about 1 dB/km.
- 19. The system of claim 15, wherein the power loss is less than about 0.5 dB/km.
- 20. The system of claim 15, wherein the cable comprises a second protective layer.
- 21. The system of claim 15, wherein the cable comprises a second cladding.
- 15 22. A coil of optical fiber cable for transmitting laser energy over great distances comprising:
 - a. a cable comprising: a core; a cladding; a coating; a first protective layer; and, a second protective layer;
 - b. the cable having a length greater than about 2 km.
 - 20 c. the cable capable of transmitting high power laser energy for its length with a power loss of less than about 2 dB/km.
 - d. the cable wound in a coil; and,
 - e. the outer diameter of the wound coil being less than about 6 m.
- 23. The coil of claim 22, wherein the coil is on a spool, wherein the high power laser
25 energy is greater than or equal to about 5 kW, the length is greater than about 1 km and the power loss is less than about 1 dB/km.
- 24. The coil of claim 22, wherein the cable length is greater than about 2 km.

25. The coil of claim 22, wherein the cable length is greater than about 3 km.
26. A system for delivering high power laser energy to a tool, the system comprising:
- a. a high power laser having a power of at least about 1 kW;
 - b. an optical fiber cable comprising:
 - 5 i. a core;
 - ii. a cladding;
 - iii. a coating; and,
 - iv. a first protective layer;
 - c. a tool;
 - 10 d. the cable having a first and second end and a length between the first and second end;
 - e. the length of the cable being greater than 0.5 km;
 - f. the first end of the cable optically associated with the laser and the second end of the cable optically associated with the tool;
 - 15 g. a laser beam having a wavelength in the range of from about 800 nm to about 2000 nm transmitted in the cable and having a power of at least about 1 kW at the first end of the cable;
 - h. the power loss of the laser beam in the cable from the first end to the second end being less than about 2 dB/km; and,
 - 20 i. where the delivered laser energy has a spectrum that is substantially free from stimulated Raman scattering.
27. The system of claim 26, wherein the laser beam has a wavelength of about 1080 nm.
28. The system of claim 26, wherein the laser beam has a wavelength of about 1550 nm.
- 25

29. The system of claim 26, wherein the laser beam has a wavelength of about 1490 nm
30. The system of claims 26, wherein the power loss is less than about 1 dB/km.
31. The system of claim 26, wherein the power loss is less than about 0.5 dB/km.
- 5 32. A system for delivering high power laser energy to a tool, the system comprising:
- a. a high power laser having a power of at least about 5 kW;
 - b. an optical fiber cable comprising:
 - i. a core; and,
 - ii. a protective layer;
 - 10 c. a tool;
 - d. the cable having a first and second end and a length between the first and second end;
 - e. the length of the cable being greater than 2 km;
 - f. the first end of the cable optically associated with the laser and the second
15 end of the cable optically associated with the tool;
 - g. a laser beam having a wavelength in the range of from about 800 nm to about 2000 nm transmitted in the cable and having a power of at least about 5 kW at the first end of the cable; and,
 - h. the power loss of the laser beam in the cable from the first end to the
20 second end being less than about 0.8 dB/km.
33. The system of claim 32, wherein the power loss is less than about 0.3 dB/km.
34. An optical fiber cable for transmitting high power laser energy over great distances comprising:
- a. a cable having an input end for receiving laser energy and an output end
25 of delivering laser energy to a tool or surface;

5

- b. the cable having a length between the input end and the output end that is at least about 1 km;
- c. the cable comprising: a core; a cladding; a coating; and a means for protection;
- d. the cable core having a diameter of at least about 300 microns;
- e. the cable input end configured to receive high power laser energy from a laser having a power greater than or equal to about 10 kW; and,
- f. the cable output end configured to deliver from the at least about 70% of the received laser energy.

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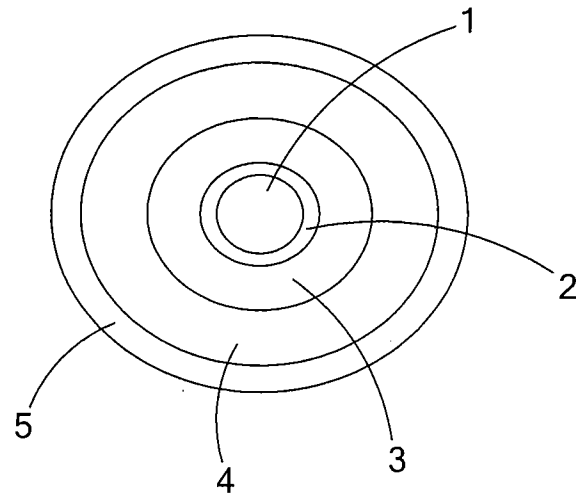


Fig. 1A

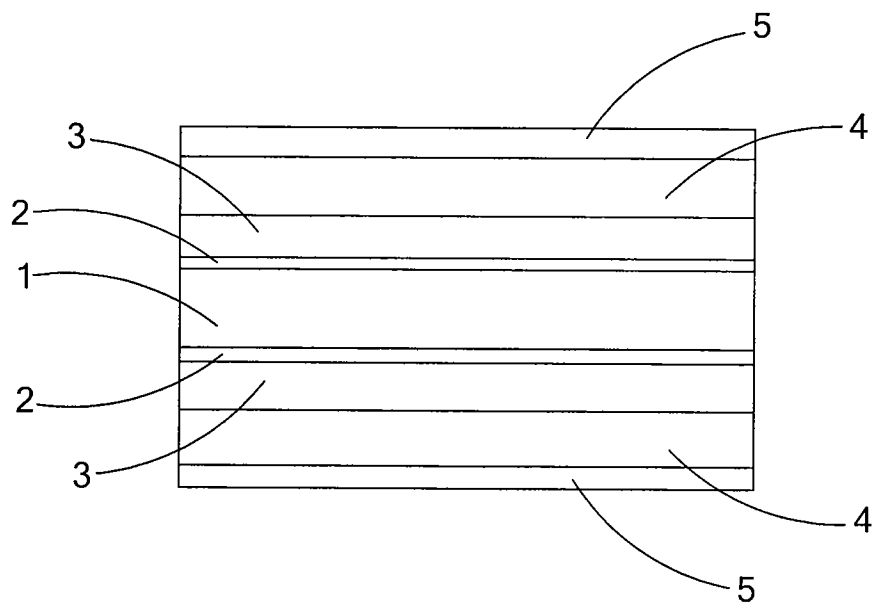


Fig. 1B

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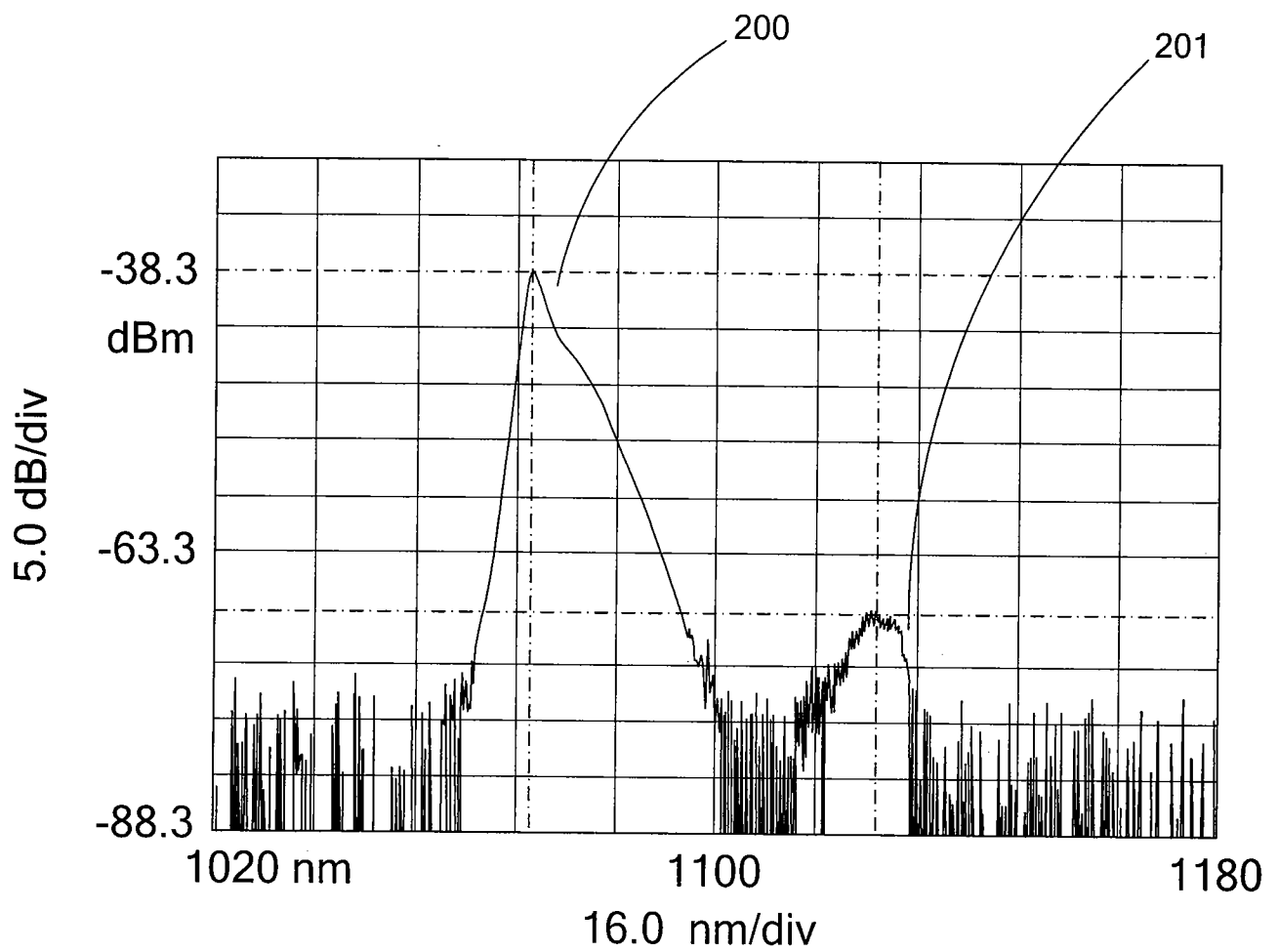


Fig. 2 (Prior Art)

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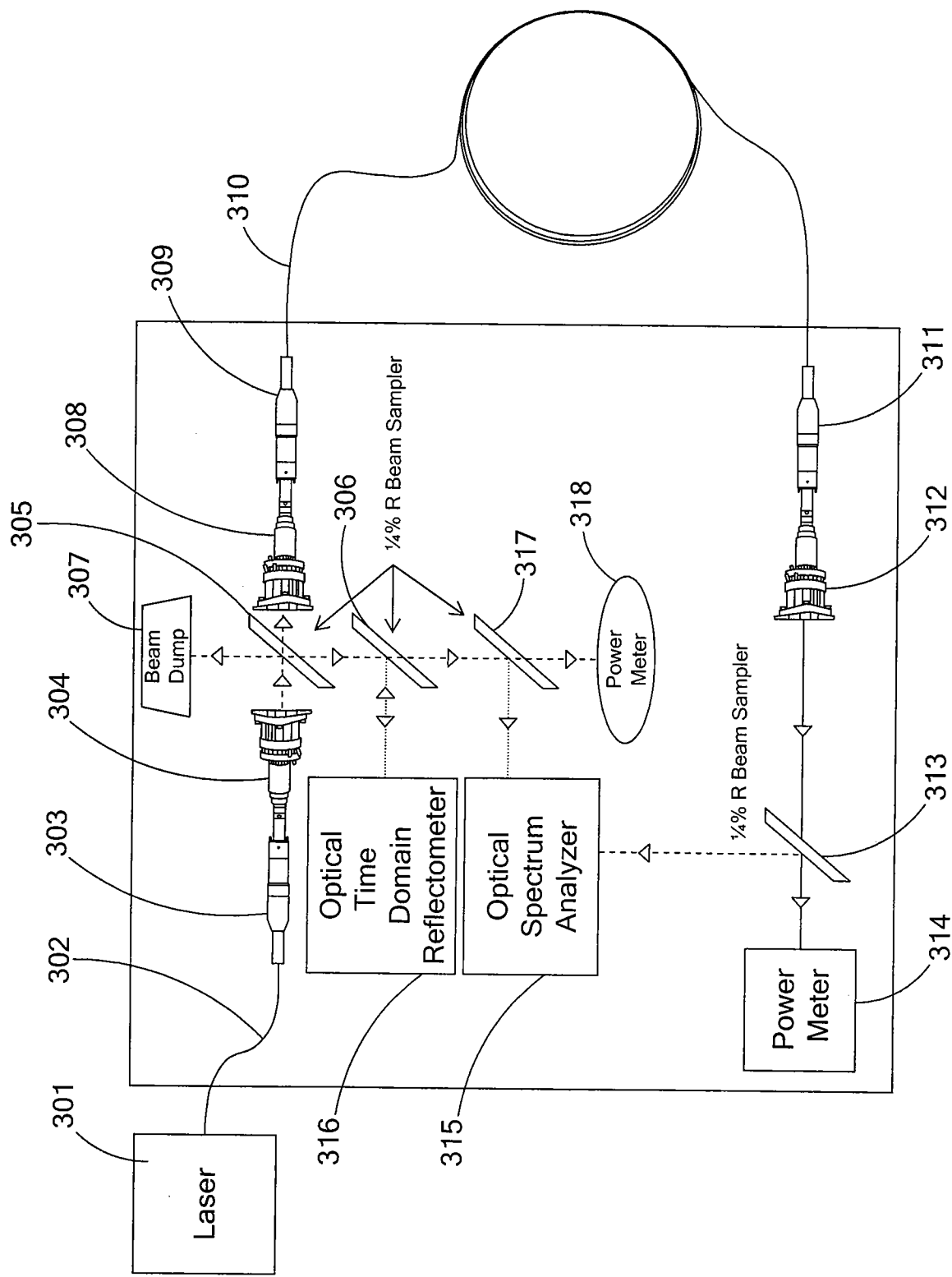


Fig. 3

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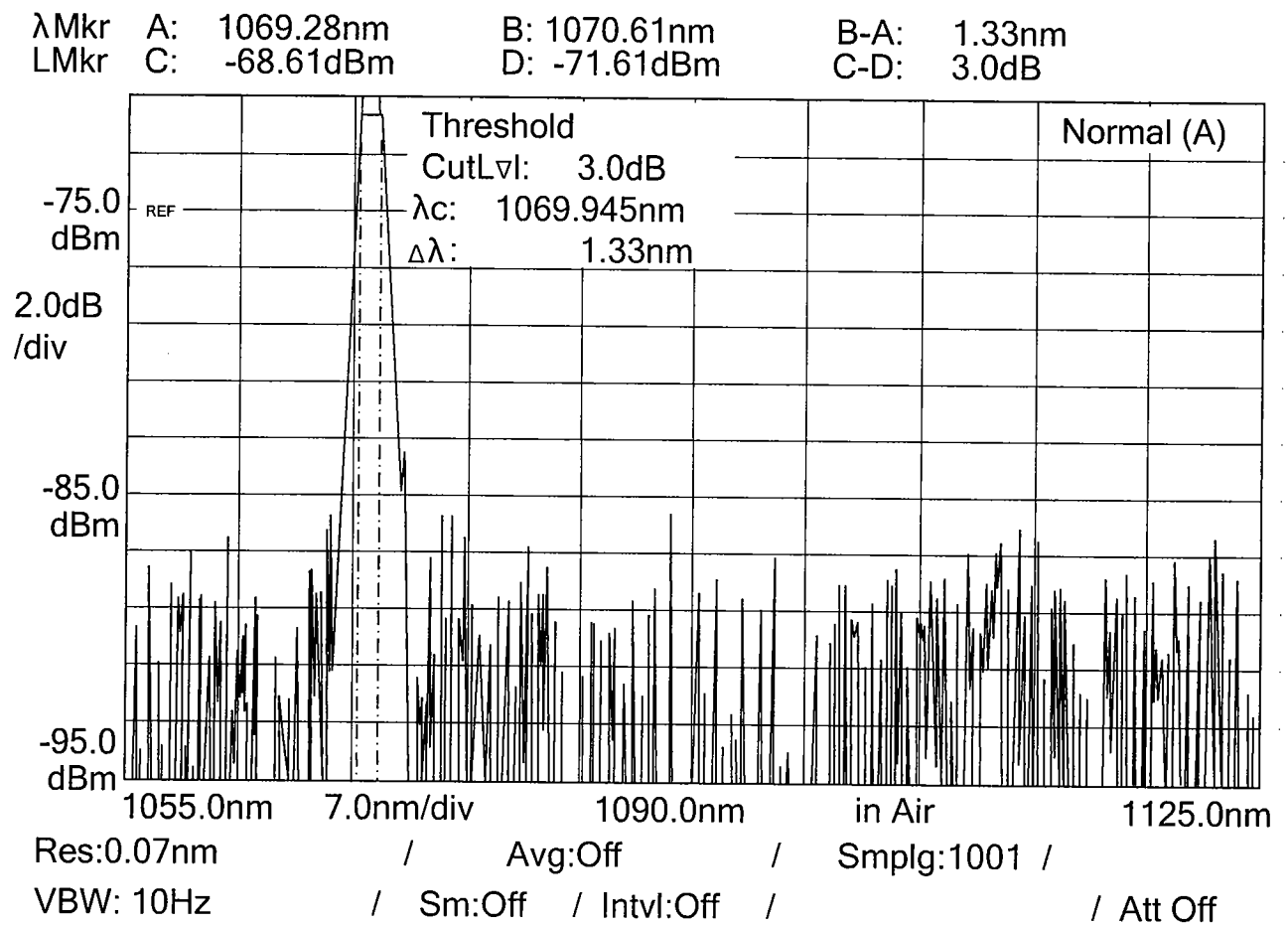


Fig. 4

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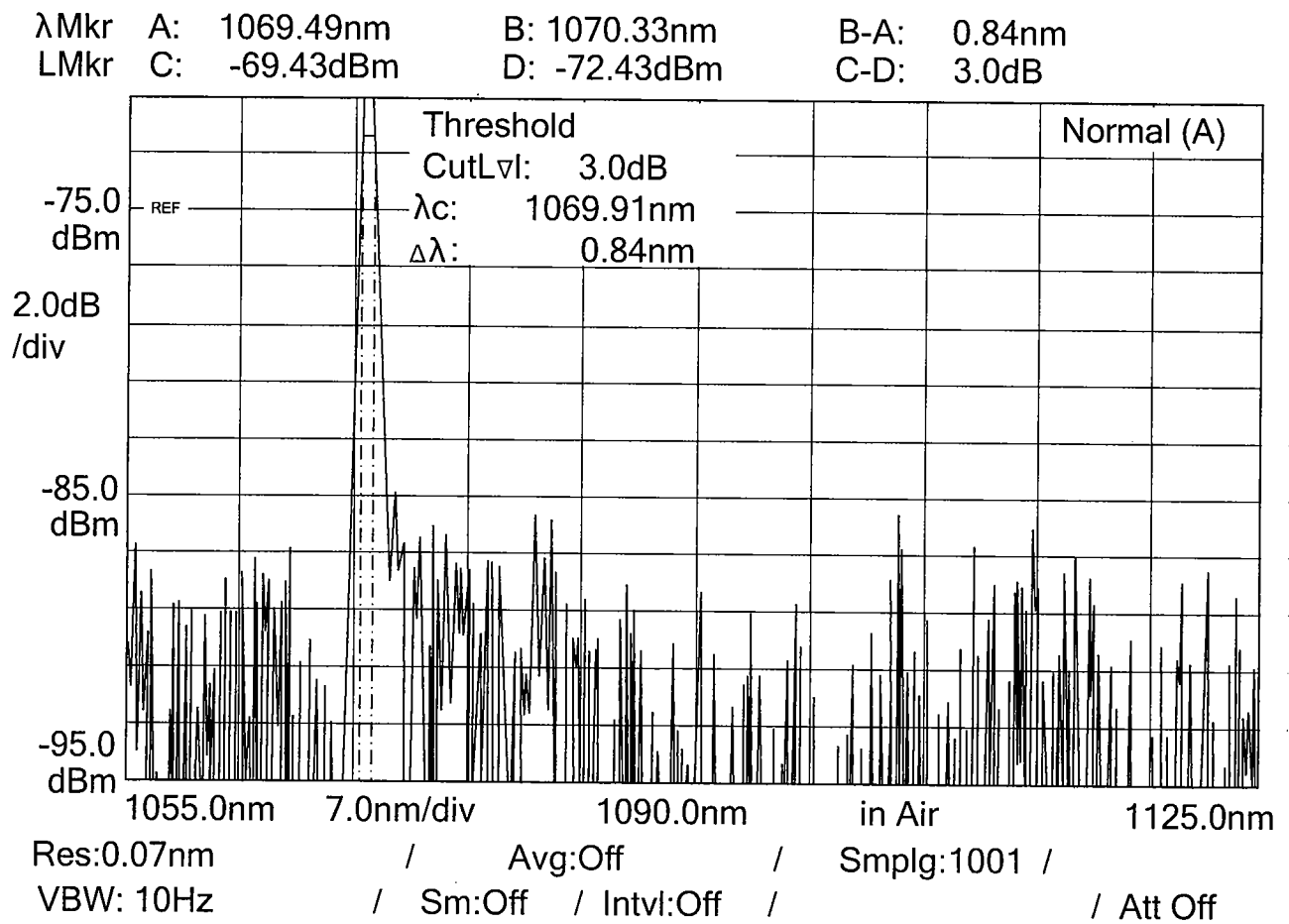


Fig. 5

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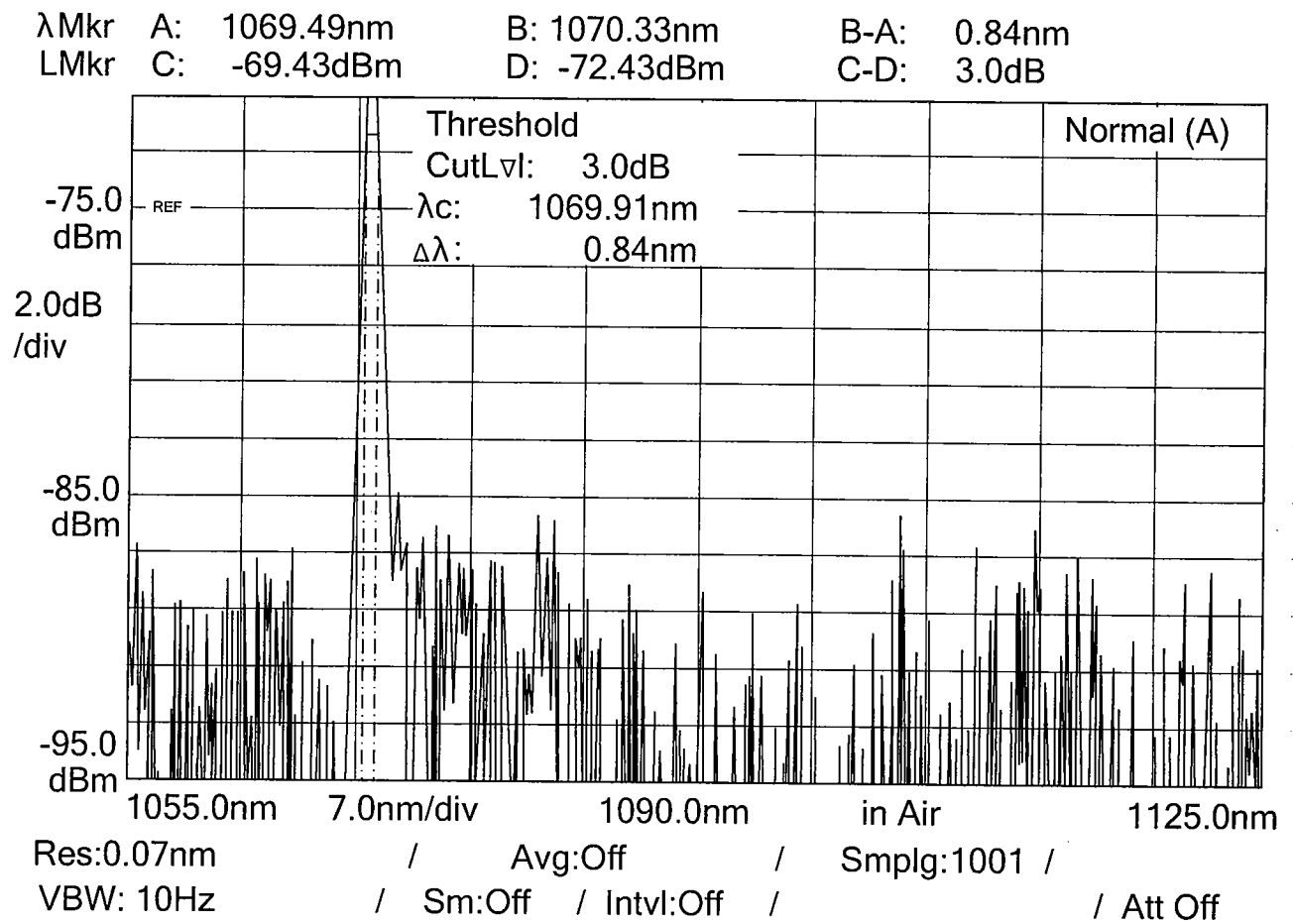


Fig. 6

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 10/24368

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - G02B 6/44 (2010.01)

USPC - 385/100

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): G02B 6/44 (2010.01)

USPC: 385/100

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

USPC: 385/1, 15, 19, 31, 33, 37, 39, 44, 53, 76, 77, 78, 88, 90, 100, 134, 139, 140, 558, 565, 566, 569 (keyword limited; 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); Google; Search Terms: fiber fibre optic fiber-optic fibre-optic laser "Light Amplification by Stimulated Emission of Radiation" electromagnetic radiation high low max peak power energy distance length range radius cable wire link line 500 1000 2000 3000 meter metre feet 0.5 1 2 3 kilometer kilometre mile power kW k

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2005/0201652 A1 (ELLWOOD JR) 15 September 2005 (15.09.2005), entire document, especially para. [0024], [0026], [0035], [0059], [0074], [0079], [0086]-[0087], [0105], [0108], [0117], [0121]-[0122]	1 - 34
Y	US 2006/0204188 A1 (CLARKSON et al.) 14 September 2006 (14.09.2006), entire document, especially para. [0003], [0025], [0040], [0052], [0055], [0057], [0083], [0086]-[0087], [0090]	1 - 34
Y	US 2007/0247701 A1 (AKASAKA et al.) 25 October 2007 (25.10.2007), entire document, especially para. [0015], [0127]	2-7, 11, 24, 25
Y	US 2008/0138022 A1 (TASSONE) 12 June 2008 (12.06.2008), entire document, especially para. [0004], [0015]	18, 19, 30, 31, 33
Y	US 2008/0180787 A1 (DIGIOVANNI et al.) 31 July 2008 (31.07.2008), entire document, especially para. [0013], [0051]-[0052], [0057], [0059]	27-29

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

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

21 October 2010 (21.10.2010)

Date of mailing of the international search report

02 NOV 2010

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