(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
22 August 2013 (22.08.2013)

WIPO | PCT

(10) International Publication Number
WO 2013/123003 A2

(51) International Patent Classification:
G01K 11/32 (2006.01)

(21) International Application Number:
PCT/US2013/025872

(22) International Filing Date:
13 February 2013 (13.02.2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
13/396,416 14 February 2012 (14.02.2012) US

(71) Applicant *(for all designated States except US)*: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 10200 Bellaire Blvd., Houston, TX 77072 (US).

(72) Inventors; and
(71) Applicants *(for US only)*: **JAASKELAINEN, Mikko** [US/US]; 4011 Bell Hollow Lane, Katy, TX 77494 (US). **MITCHELL, Ian** [US/US]; 5303 S. Mason Rd., #2224, Houston, TX 77450 (US).

(74) Agent: **ERVIN, Michael, A.**; 8202 Talbot Cove, Austin, TX 78746 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

[Continued on next page]

(54) Title: SUPPRESSION OF STIMULATED RAMAN SCATTERING

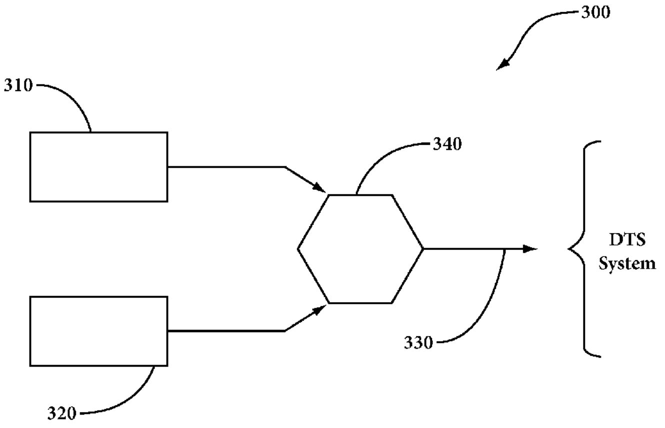

FIG 3

(57) Abstract: An apparatus, method, and system for suppressing stimulated Raman scattering (SRS) in fiber optic distributed temperature sensing systems by use of a combination of a pump and seed lasers with chosen frequency differences.

WO 2013/123003 A2

- *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*
- *of inventorship (Rule 4.17(iv))*

Published:

- *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

Title of the Invention

Suppression of Stimulated Raman Scattering

Cross-Reference to Related Applications

[001] This application claims the priority of U.S. application number 13/396,416 filed on February 14, 2012.

Background

[002] This disclosure relates generally to distributed temperature sensing (DTS) systems and, more particularly, to methods and systems for extending the range of fiber optic DTS systems.

[003] For several years, fiber optic sensors, and in particular DTS systems, have provided higher bandwidth, inherently safe operation (no generation of electric sparks), and immunity from EMI (Electromagnetic Interference) for parameter measurements.

[004] For example, the temperature profile parameter and other parameter profiles along the fiber can be monitored. The resulting distributed measurement is equivalent to deploying a plurality of conventional point sensors, which would require more equipment and increase operational costs. Each conventional electrical point sensor would require multiple electrical leads and this would add to a large and expensive cable bundle as the number of point sensors increase.

[005] When an optical fiber is excited with a laser light having a center wavelength λ, most of the light is transmitted. However, small portions of incident light λ and other excited components are scattered backward and forward along the fiber. The amplitude of the other excited components depends on the intensity of the light at center wavelength **λ** and the properties of the optical fiber. In the measurement of distributed temperature using Raman scattering, three components are of particular interest. The three components are Rayleigh back-scattered light, which will have a similar wavelength λ as the original laser wavelength, Raman Stokes and Raman anti-Stokes components which have longer and shorter wavelengths than the original wavelength **λ**. These three components can be separated by optical filters and received by photo detectors to convert light to electrical signals. A ratio between the temperature sensitive Raman anti-Stokes intensity to the temperature insensitive Rayleigh or largely temperature insensitive Raman Stokes intensity forms the basis of a Raman based distributed temperature measurement.

[006] One problem with current systems and techniques is the ability to measure these parameter profiles over an extended distance, where the optical signal tends to degrade due to the attenuation along the fiber. In conventional fiber optic Raman based DTS systems, as an example, when the intensity of the input light is increased, the Raman Stokes and Raman anti-Stokes respective power in the optical fiber increases as well. This phenomenon is called Spontaneous Raman Scattering. When the input power of the optical source is further increased above a threshold level, stimulated scattering may occur either due to Brillouin scattering or Raman scattering. Stimulated Brillouin scattering manifests itself through the generation of a backward propagating Brillouin Stokes wave that carries most of the input energy once the Brillouin threshold is reached. The threshold level depends on light source properties such as peak power and spectral width, and optical fiber properties such as chemical composition of the fiber, Numerical Aperture and mode field diameter. Once the Brillouin threshold is reached, increased backward propagating non-linear stimulated Brillouin Stokes light may saturate the detector while limiting the amplitude of the forward propagating light. For these reasons, increasing the light energy by increasing the laser power is not a viable approach to increasing the distance reach for a conventional DTS system as the increase in signal energy is back scattered. Stimulated Brillouin scattering is often what limits the maximum power that can be transmitted into optical fibers using narrow line-width high power lasers.

[007] Similarly, stimulated Raman scattering transfers energy in a non-linear fashion from the center light wavelength λ to the Raman Stokes component. As a result, the ratio between Raman Stokes and Raman anti-Stokes varies without temperature changes, thus generating errors in temperature calculations. Data taken in the fiber length where non-linear stimulated interactions occur tends to generate significant errors in temperature calculations.

[008] Other attempts to solve this problem rely on the use of special filters in the fiber line to remove stokes components. Due to the sensitivities of Raman DTS to changes in power levels this approach tends to introduce inaccuracies into the temperature calculation. There have also been attempts to use stimulation to create a main pulse that extends further out into the fiber in single laser STS but these solutions do not work close to the beginning of the fiber and have the problem of not having a reference temperature to tie the trace to. This also makes calibration very difficult.

[009] Hartog et al disclosed a scheme (US Pat 7,304,725) based on a sensing system composed of two sequential physically different fibers with different Numerical Apertures to avoid this effect. They also disclosed another system, in which an optical amplifier (more precisely a length of rare-earth doped fiber in a section of the sensing fiber) was placed in between two sensing fibers to boost up the attenuated input optic energy to reach further distance.

[0010] Such approaches introduce cost and complexity in both design and operation. Accordingly, systems and methods that provide for extending the range of fiber optic DTS systems without undue complexity in the sensing fiber design and deployment are desired. Methods that suppress the Stokes wave build-up rather than actively filtering the Stokes wave as it builds up would be preferable.

Brief Description Of The Drawings

[0011] Figure 1 is a block diagram of one example of a distributed temperature sensing system.

[0012] Figure 2 exhibits some of the typical spontaneous backscattered Raman signals received from a distributed temperature sensing system.

[0013] Figure 3 is a block diagram of a system of this application configured to create suppression of stimulated Raman signals.

[0014] Figure 4 is a graphical diagram showing a mathematical simulation of the pump and stokes power from launching a single high power pump pulse.

[0015] Figure 5 is a bar graph representation of the power profiles from Figure 4 for initial launch and then the later beam profile much further out in the fiber.

[0016] Figure 6 is a graphical diagram showing a mathematical simulation of the pump and stokes power from launching a dual high power pump pulses.

[0017] Figure 7 is a bar graph representation of the power profiles from Figure 6 for initial launches and then the later beam profile much further out in the fiber.

Detailed Description

[0018] In the following detailed description, reference is made that illustrate embodiments of the present disclosure. These embodiments are described in sufficient detail to enable a person of ordinary skill in the art to practice these embodiments without undue experimentation. It should be understood, however, that the embodiments and examples described herein are given by way of illustration only, and not by way of limitation. Various substitutions, modifications, additions, and rearrangements may be made that remain potential applications of the disclosed techniques. Therefore, the description that follows is not to be taken in a limited sense, and the scope of the disclosure is defined only by the appended claims.

[0019] The concept described herein is to use a seed laser pulse in conjunction with the pump (primary) laser pulse and to pulse them simultaneously into a fiber optic distributed temperature sensing system with the laser sources chosen with certain specific frequency difference characteristics.

[0020] An apparatus for use in a fiber optic distributed temperature sensing (DTS) system for suppressing stimulated Raman scattering in fiber optic cables can include at least a primary pump laser source for pulsing a primary light signal for distributed temperature system measurements; a secondary seed laser source for pulsing a secondary light signal; and a wavelength division multiplexer (WDM) for receiving the primary light signal and the secondary light signal and passing the resulting signal into a distributed temperature sensing system.

[0021] A method for suppressing stimulated Raman scattering in fiber optic cables in a distributed temperature sensing (DTS) system can include at least the steps of feeding a primary pump laser source for a distributed temperature sensing system through a lead fiber and into a wavelength division multiplexer (WDM); feeding a secondary seed laser source through a lead fiber and into the wavelength division multiplexer; and feeding the resultant light from the wavelength division multiplexer into a fiber optic distributed temperature sensing system.

[0022] Figure 1 illustrates a conventional DTS system, including a light source **10**, a lead light fiber **11**, a light splitter and combiner **12**, lead fiber **13**, a sensing fiber **14**, optical spectrum separator 16, and a reference fiber coil **22**. Light source **10** provides optical signal through lead fiber **11** which may reach sensing fiber **14** via light splitter/combiner **12**, reference fiber coil **22**, and lead fiber **13**. During the transmission of optical signal to sensing fiber **14**, a portion of the light may be scattered and may travel back to optical spectrum separator **16** via lead fiber **13**, light splitter/combiner **12**, and lead fiber **15**. The backscattered light from the sensing fiber may include light components such as Rayleigh component **17** (same center wavelength as injected light), Brillouin Stokes component **18** and Brillouin Anti-Stokes component **19**, Raman Stokes component **20**, and Raman Anti-Stokes component **21**, all of which may be separated via optical spectrum separator **16**. Raman Stokes **20** and Raman anti-Stokes **21** (collected Raman scatterings) may be shifted from the input wavelength of the optical signal and be mirror imaged about Rayleigh component **17**, as shown in Figure 2.

[0023] Reference fiber coil **22** of the DTS system may be used as a reference profile for the entire temperature profile of the sensing fiber. For other profiles, reference fiber coil **22** may be used as a reference point to compare or analyze measured points.

[0024] In one embodiment, the Raman components may be used to determine parameter profiles such as temperature profiles. The Raman Stokes and Raman Anti-Stokes band are typically separated by more than tens of nanometers, whereas Brillouin components **18** and **19** are much closer - less than 0.1 nanometer from the Rayleigh bandwidth, as shown in Figure 2. In particular, the temperature may be inversely proportional to the intensity of Raman Stokes component **20** over the intensity of Raman Anti-Stokes component **21**.

[0025] Due to the nature of the optical sensing fiber, the transmitted light energy is decreased (or attenuated) as it travels through the fiber. As a result, the signal to noise ratio is lowered, which may cause a degradation of the temperature resolution towards the far end of the fiber. One way to solve this problem is to launch higher power laser light to increase the optical energy. However, as discussed earlier, this generates stimulated scattering and induces non-linearity, which degrades the accuracy and/or resolution of the DTS system.

[0026] In an aspect of this invention a second seed laser pulse at a second Raman frequency (26 THz shift) can be propagated along with the main pulse. In this aspect as the Stokes wave at 13 THz shift begins to grow, the light is re-stimulated to the next Raman band at the seed wavelength. In this way the Stokes wave is never allowed to fully form ands so stimulation from the main pulse is suppressed.

[0027] A simple configuration to carry out the invention is illustrated in Figure 3, illustrated by the numeral **300**, in which a primary light source **310** (for example a 1064nm wavelength pulsed laser) is combined with a seed light source **320** (for example an 1170nm wavelength pulsed laser) and fed through a lead fiber **330** into a wavelength division multiplexer (WDM) **340** where the two pulses are combined and then fed into a DTS system. A number of different DTS system configurations could be used – the example one in Figure 1 is one example. Using that as an example source **10** in Figure 1 would be replaced with configuration **300** of Figure 3. The two pulsed lasers would be fired simultaneously so that their signals overlap and travel through WDM **340** and into the remainder of the DTS system together.

[0028] As mentioned previously, when a single laser power is increased to measure over longer distances a regime of stimulated Raman scattering is encountered which introduces non-linearity. It is useful to first show how this occurs when only the pump laser is used at high power to cover a large distance. Figure 4 is a mathematical simulation of how the laser powers change over a distance of 10km with a single pump power at 1064 nanometers wavelength is used. The curve **410** represents the relative power of the 1064 nm pulse wave as it travels down the fiber and shows the depletion of that wave as the Stokes wave **420** rapidly grows from the stimulated scattering.

[0029] Figure 5 exhibits this phenomena in a bar graph form in which the initial beam profile, which is all pump pulse **510** at 1064 nm is shown on the left hand side of the graph. Much further out a late beam profile is shown in which the initial 1064 nm wavelength pulse **520** is now severely attenuated as it's energy is transferred into the stimulated Stokes signal **530** at 1115 nm. The non-linear and large Stokes signal **530** is strong enough that it generates it's own further Stokes signal **540** at 1170. A further very small Stokes signal **550** is generated at 1245 nm. These secondary Stokes signals are too small to be clearly seen on Figure 4. As a result of the large Stokes component **530** at 1115 nm, the ratio between Raman Stokes and Raman anti-Stokes varies without temperature changes, thus generating errors in temperature calculations. Data taken in the fiber length where non-linear stimulated interactions occur can generate significant errors in temperature calculations.

[0030] Figure 6 is an alternate mathematical simulation in which both of the lasers shown in Figure 3 are fired simultaneously. The two wavelengths of 1064 nm and 1170 nm represent a Raman frequency shift of approximately twice the Raman frequency shift of 13 THz. They are fired in this simulation at identical power. With this combination the seed pulse **610** at 1170 nm generates a stimulated seed Stokes **620** at 1245 nm but in doing so suppresses the stimulated Raman scattering of the pump pulse **600** with the result that the pump stokes **630** at 1115 nm grows in the normal simultaneous manner. As that pump Stokes **630** begins to grow, the light is re-stimulated to the next Raman band at the seed wavelength of 1170 nm.

[0031] This is illustrated further in Figure 7 in which the phenomena are illustrated in a bar graph similar to the previous bar graph of figure 5. The initial beam profile on the left hand side shows the two identical power lasers – the pump pulse **710** at 1064 nm and the seed pulse **720** at 1115 nm. In the late beam profile it can be seen that unlike Figure 5 in which the pump pulse is severely depleted – in Figure 7 the pump pulse **730** at 1064 nm is still substantial because stimulated Raman scattering of the pump pulse has been suppressed and the pump stokes **740** at 1115 nm is now a normal signal that can be used in conjunction with the anti-Stokes signal (not shown) in performing distributed temperature sensing calculations to much greater distances. The seed pulse **750** introduced in the initial profile at 1115 nm though has now experienced stimulated Raman scattering as evidenced in the severely depleted 1170 nm signal accompanied by an enlarged 1245 nm signal **760** that is the seed Stokes signal. This seed Stokes signal is enlarged and non-linear in response but is ignored and not used in any of the DTS calculations. The net effect is the desired suppression of stimulated Raman scattering of the pump pulse.

[0032] By the use of this method and apparatus the upper power ceilings can be increased by an order of magnitude providing unmatched range and resolution for long distance measurement of temperatures in DTS systems.

[0033] Although certain embodiments and their advantages have been described herein in detail, it should be understood that various changes, substitutions and alterations could be made without departing from the coverage as defined by the appended claims. Moreover, the potential applications of the disclosed techniques is not intended to be limited to the particular embodiments of the processes, machines, manufactures, means, methods and steps described herein. As a person of ordinary skill in the art will readily appreciate from this disclosure, other processes, machines, manufactures, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufactures, means, methods or steps.

Claims

1. An apparatus for use in a fiber optic distributed temperature sensing (DTS) system for suppressing stimulated Raman scattering in fiber optic cables comprising:
    a. a primary pump laser source for pulsing a primary light signal for distributed temperature sensing system measurements;
    b. a secondary seed laser source for pulsing a secondary light signal; and
    c. a wavelength division multiplexer (WDM) for receiving said primary light signal and said secondary light signal and for passing the resulting signal into a distributed temperature sensing system.
2. The apparatus of claim 1 wherein said primary pump laser source has approximately a 26 THz higher frequency than said secondary seed laser source.
3. The apparatus of claim 1 wherein said primary pump and said secondary seed laser sources deliver approximately the same power level.
4. The apparatus of claim 1 wherein said primary pump laser source is a 1064 nanometer laser.
5. The apparatus of claim 1 wherein said secondary seed laser light source is a 1170 nanometer laser.
6. A method for suppressing stimulated Raman scattering in fiber optic cables in a distributed temperature sensing (DTS) system comprising the steps of:
    a. feeding a primary pump laser source for a distributed temperature sensing system through a lead fiber and into a wavelength division multiplexer (WDM);
    b. feeding a secondary seed laser source through a lead fiber and into said wavelength division multiplexer; and

   c. feeding the resultant light from the wavelength division multiplexer into a fiber optic distributed temperature sensing system.

7. The method for suppressing stimulated Raman scattering in fiber optic cables in a distributed temperature sensing (DTS) system of claim 6 wherein said primary pump laser source has approximately a 26 THz higher frequency than said secondary seed laser source.
8. The method for suppressing stimulated Raman scattering in fiber optic cables in a distributed temperature sensing (DTS) system of claim 6 wherein said primary pump and said secondary seed laser sources deliver approximately the same power level.
9. The method for suppressing stimulated Raman scattering in fiber optic cables in a distributed temperature sensing (DTS) system of claim 6 wherein said primary pump laser source is a 1064 nanometer laser.
10. The method for suppressing stimulated Raman scattering in fiber optic cables in a distributed temperature sensing (DTS) system of claim 6 wherein said secondary seed laser source is a 1170 nanometer laser.
11. A system for use in a fiber optic distributed temperature sensing (DTS) system for suppressing stimulated Raman scattering in fiber optic cables comprising:
    a. a means for using a primary pump laser source for pulsing a primary light signal for distributed temperature sensing system measurements;
    b. a means for using a secondary seed laser source for pulsing a secondary light signal; and
    c. a means for using a wavelength division multiplexer (WDM) for receiving said primary light signal and said secondary light signal and for passing the resulting signal into a distributed temperature sensing system.

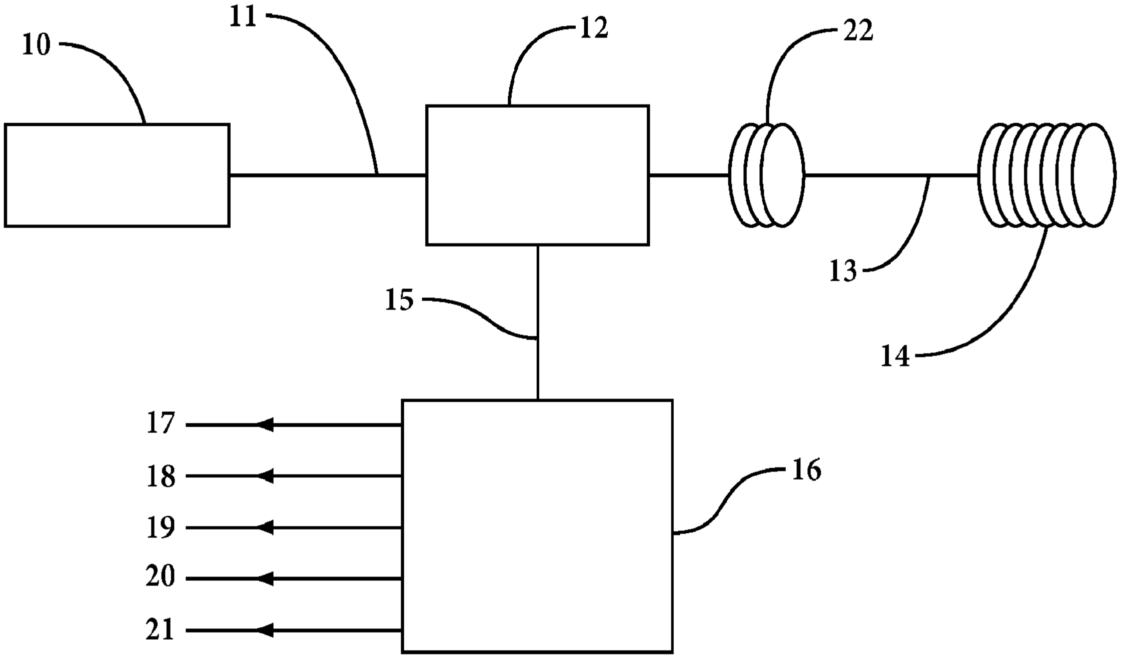

FIG 1

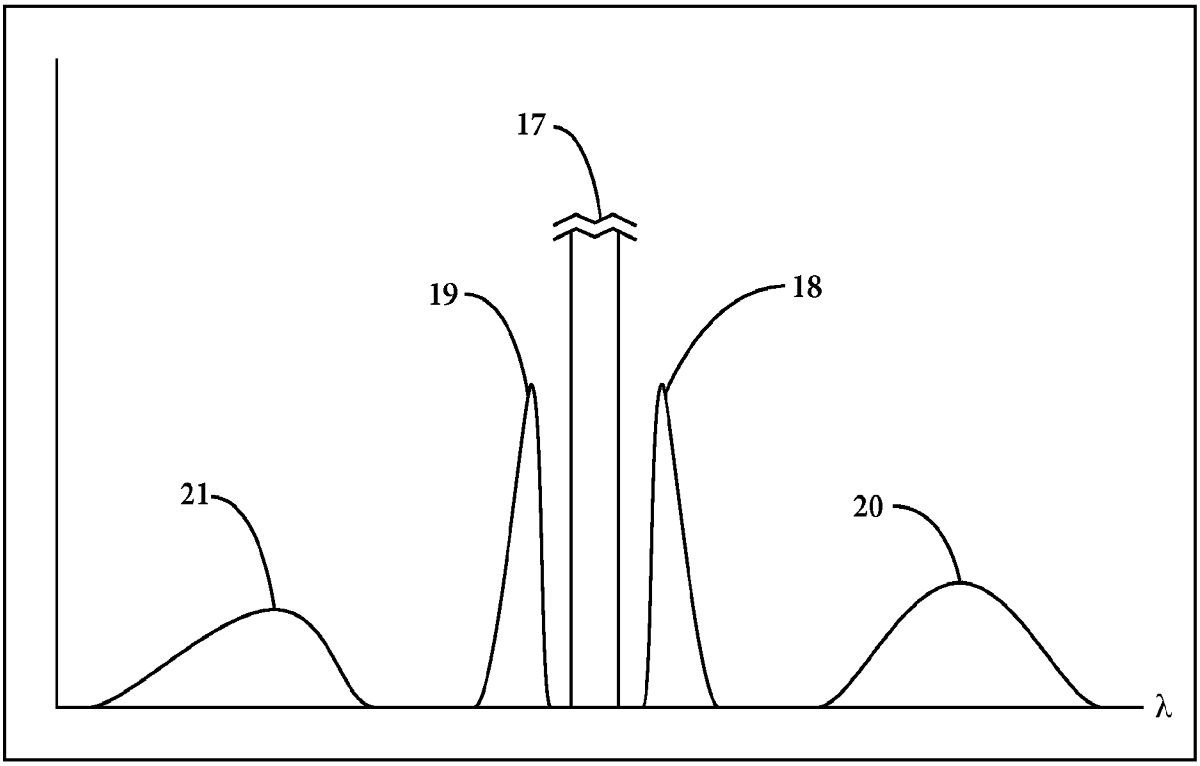

FIG 2

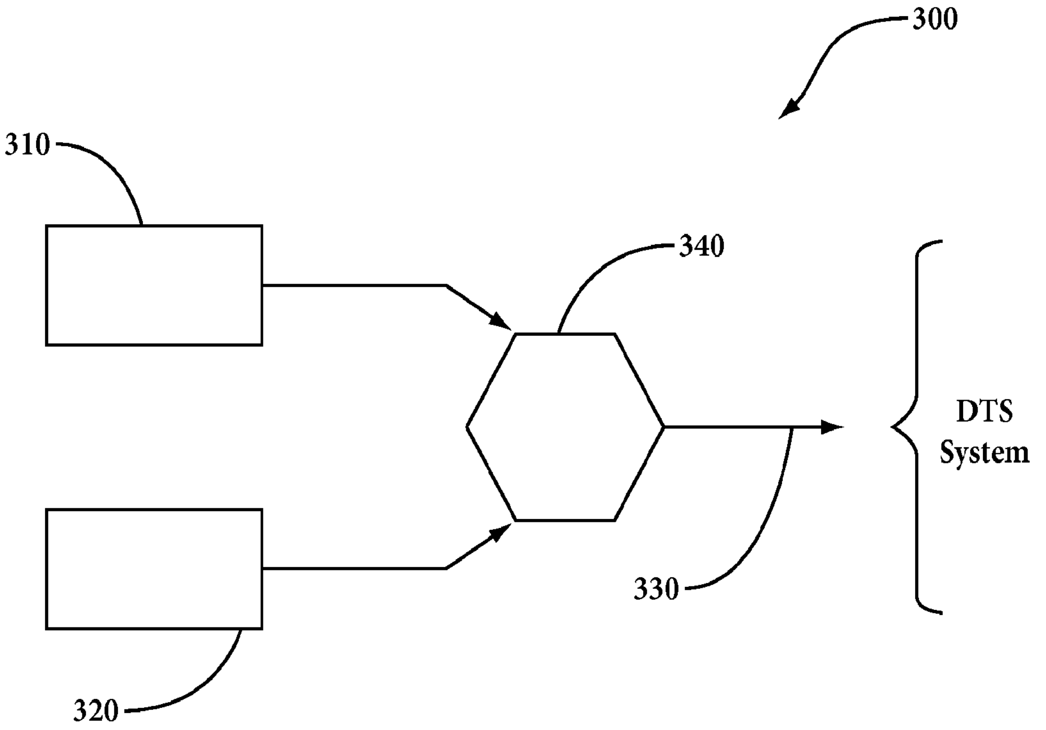

FIG 3

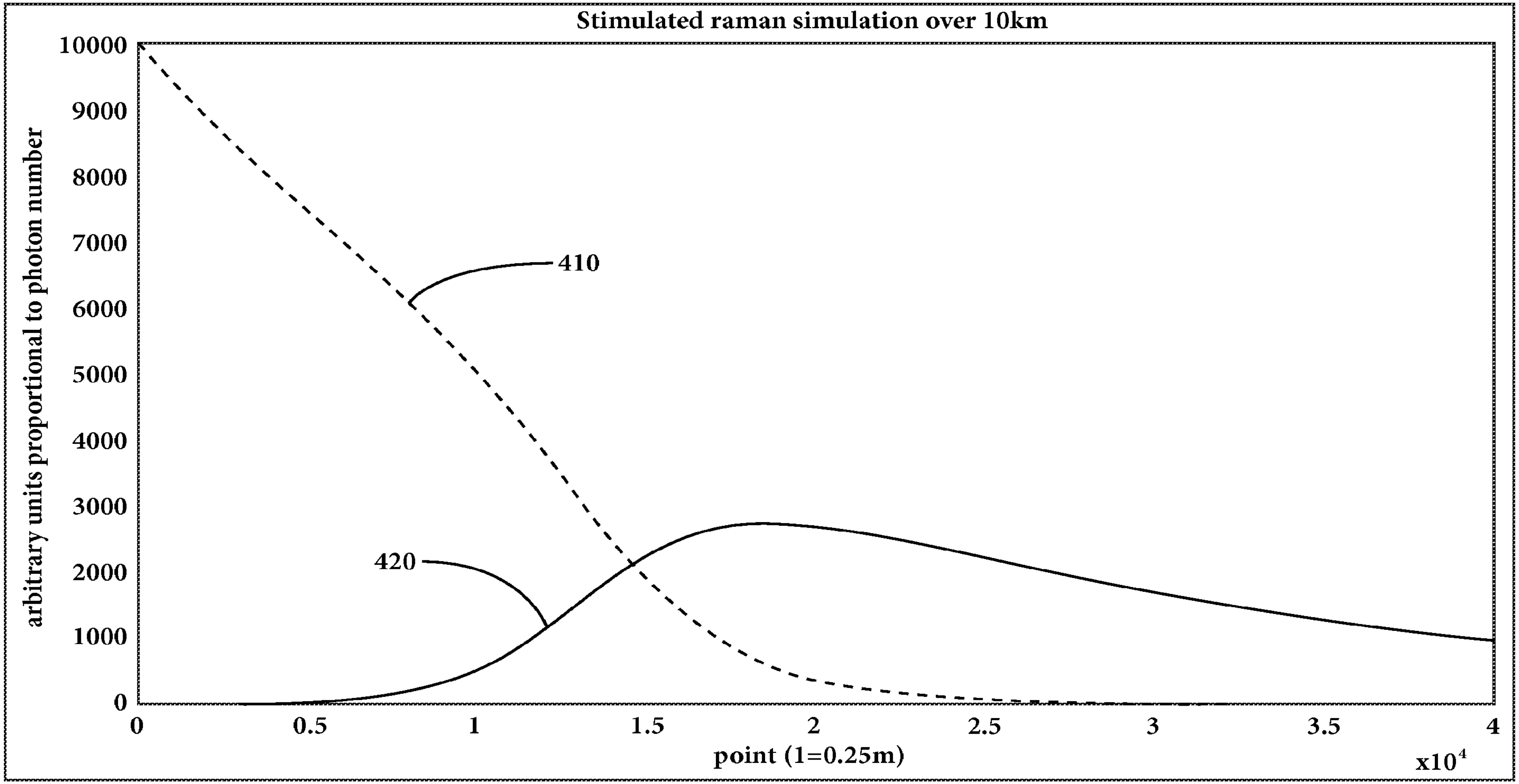
Stimulated raman simulation over 10km
arbitrary units proportional to photon number
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
point (1=0.25m)
x10^4
410
420

FIG 4

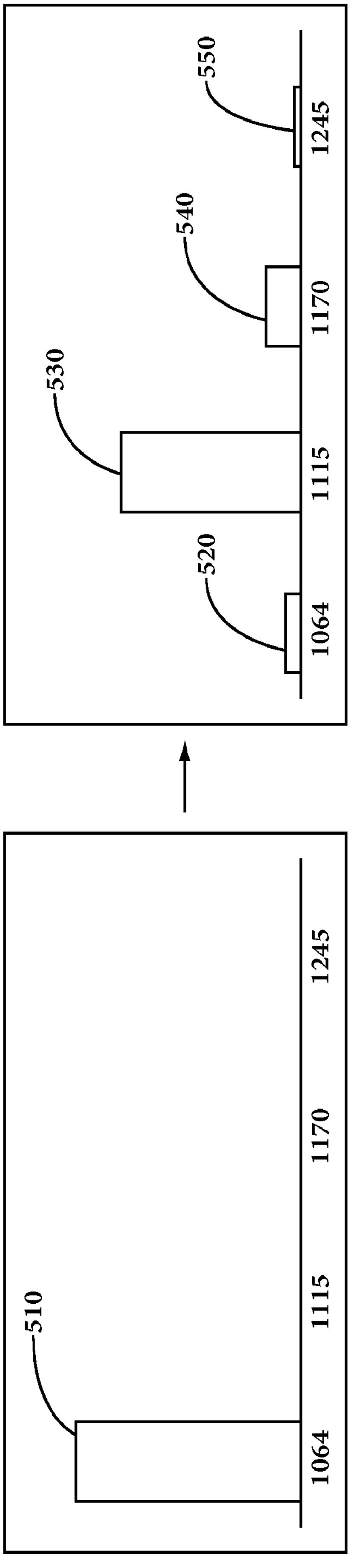

FIG 5

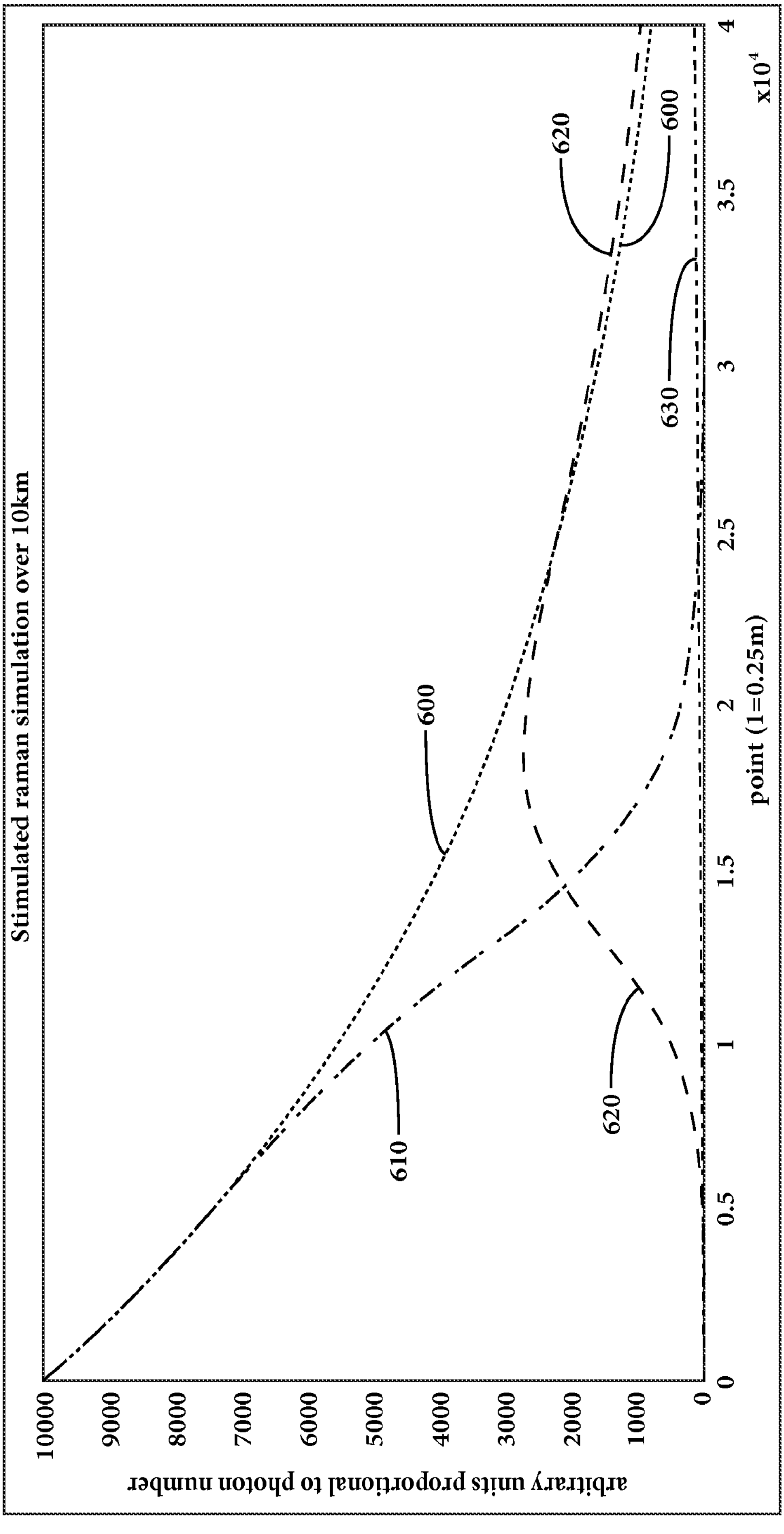
Stimulated raman simulation over 10km
arbitrary units proportional to photon number
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.5
1
1.5
2
2.5
3
3.5
4
x10⁴
point (1=0.25m)
600
610
620
620
600
630

FIG 6

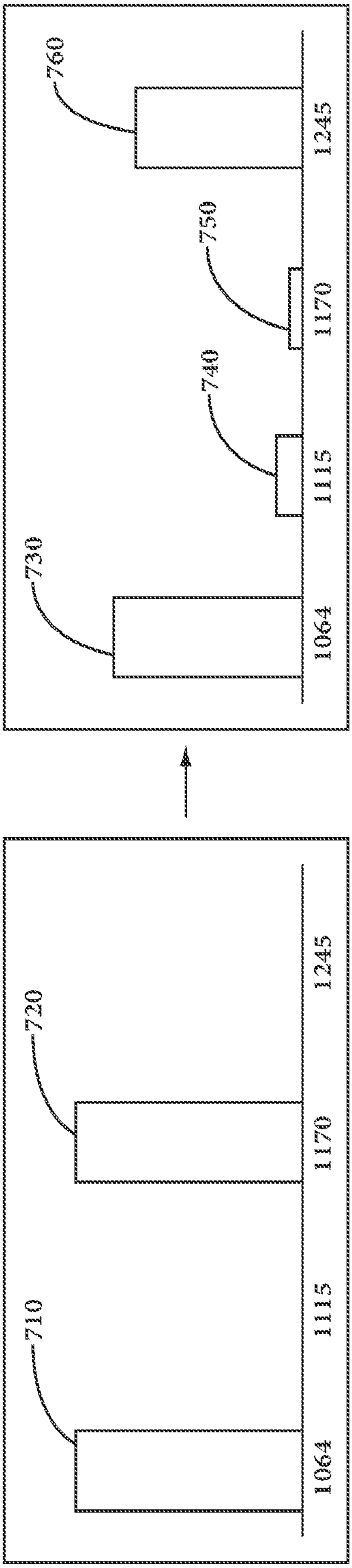
710
720
1064
1115
1170
1245
730
740
750
760
1064
1115
1170
1245

FIG 7