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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
8 September 2017 (08.09.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/151090 A1

(51) International Patent Classification:
E21B 47/12 (2006.01) *E21B 17/00* (2006.01)
E21B 47/135 (2012.01)

(21) International Application Number:
PCT/US2016/020038

(22) International Filing Date:
29 February 2016 (29.02.2016)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 3000 N. Sam Houston Parkway E., Houston, TX 77032-3219 (US).

(72) Inventors: **VEERAVALLI MURALI, Srividhya**; 2250 Eldridge Parkway, Apt. #1024, Houston, TX 77077 (US). **STARK, Daniel, Joshua**; 8423 Hearth Drive #3, Houston, TX 77054 (US). **WONG, David, Yan Lap**; 17527 Pebble Farms Court, Humble, TX 77346 (US). **WIECEK, Boguslaw**; 2318 Cumberland Oak Ct., Kingwood, TX 77345 (US).

(74) Agents: **PATEL, Niraj, P.** et al.; Krueger Iselin LLP, P.O. Box 1906, Cypress, TX 77410-1906 (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, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, 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, SA, 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, ST, 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, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

(54) Title: FIXED-WAVELENGTH FIBER OPTIC TELEMETRY

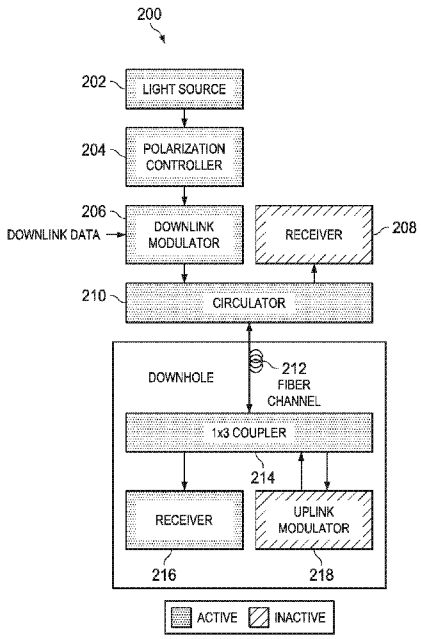


FIG. 2A

(57) Abstract: A system, in some embodiments, comprises: a light source; a fiber optic cable coupled to surface equipment and to downhole equipment and illuminated with fixed-wavelength light by said light source; and a modulator to modulate said fixed-wavelength light in the fiber optic cable to communicate data between the surface equipment and the downhole equipment, wherein the modulator uses a modified half-duplex telemetry scheme.

WO 2017/151090 A1

FIXED-WAVELENGTH FIBER OPTIC TELEMETRY

BACKGROUND

Various tools are deployed downhole to collect data pertaining to subterranean formations. Collected data can be stored in the tool or elsewhere in a drill string or slickline sonde that houses the tool. In such systems, the data is often recovered when the storage is raised to the surface. Alternatively, data may be transmitted to the surface as it is collected. Different telemetry techniques may be employed to transmit data from the tool in the wellbore to the surface. Similar telemetry techniques can be used to transmit data from the surface to the tool in the wellbore. Current telemetry techniques, however, use expensive, unnecessary equipment and suffer from technical shortcomings that adversely impact communication quality.

BRIEF DESCRIPTION OF THE DRAWINGS

Accordingly, there are disclosed in the accompanying drawings and in the following description various fixed-wavelength fiber optic telemetry systems. In the drawings:

Figure 1 is a schematic diagram of an illustrative slickline or wireline application.

Figures 2-11 are block diagrams of various fixed-wavelength fiber optic telemetry systems.

Figure 12 is a flow diagram of a method for communicating signals via the fixed-wavelength fiber optic telemetry systems of Figures 2-11.

DETAILED DESCRIPTION

Disclosed herein is a fiber optic telemetry system—usable in both slickline and wireline applications—that employs fixed-wavelength light to communicate data between downhole equipment and surface equipment. The system includes any suitable downhole equipment, such as a tool that obtains measurements pertaining to subterranean formations. The system includes processing equipment (e.g., amplifiers, microprocessors, digitizers) that process the signal to be transmitted. The processing equipment couples to a fiber optic cable that is illuminated using any appropriate type of fixed-wavelength light source, such as a fixed-wavelength laser or a fixed-wavelength light emitting diode (LED). The processing equipment modulates the fiber optic light with the digitized signal using any suitable modulation technique, such as pulse frequency modulation or phase modulation. In some embodiments, the signal is not digitized and the fiber optic light is intensity-modulated (e.g., amplitude modulated) or phase modulated.

In any case, the fiber optic cable transports the modulated light from the downhole equipment to the surface equipment or vice versa, where the light is demodulated and processed to reconstruct the original data signal. Although this technique may primarily be applied in the wireline and slickline contexts, it may be adapted for implementation in other contexts (e.g., wired drill pipe, production tubing, permanent well integrity monitoring) as well.

The use of fixed-wavelength light mitigates the wavelength filtering problems that arise in some such variable-wavelength systems. In addition, illuminating the fiber optic cable using fixed-wavelength light reduces the number of components necessary in the system. For instance, multiple light sources and/or multiple fiber optic cables are no longer required. Thus, both communication quality and cost efficiency improve.

Fig. 1 provides a side elevation view of a well 10 with an illustrative wireline tool system 14 including surface equipment and downhole equipment. The downhole equipment includes a sonde 12 suspended in the well 10 at least in part by a cable 18 having one or more optical fiber(s) 20. The well 10 is cased with a casing string 16 having casing sections 30A and 30B connected end-to-end by a collar 32. As is typical, the casing sections 30A, 30B of the casing string 16 and the collars connecting the casing sections 30A, 30B (e.g., the collar 32) are made of steel, an iron alloy, and hence it exhibits a fairly high magnetic permeability and a relatively low magnetic reluctance. In other words, the casing string material conveys magnetic field lines much more readily than air and most other materials. The illustrated sonde 12 houses a tool 22. Surface equipment 28 is coupled to the sonde 12 via the cable 18 containing optical fibers and configured to receive optical signals from the sonde 12 via the optical fiber(s) 20.

In the embodiment of Fig. 1, the tool 22 is configured to generate an electrical data signal based on the detection of some entity or measurement of some quantity in the surrounding formation. The tool 22 converts the electrical signal into an optical signal, and transmits the optical signal to the surface unit 28 via the optical fiber(s) 20 of the cable 18. In some embodiments, a signal generated by the tool 22 is converted into an optical signal and transmitted to the surface by components external to the tool 22. The tool 22 is not limited to any particular functionality and may include, for instance, a casing collar locator (CCL), a caliper, a porosity tool, a permeability tool, a resistivity tool, etc. Similarly, the scope of this disclosure is not limited to one-way communications. To the contrary, the downhole equipment (such as the tool 22) may send signals to the surface and surface equipment may send signals downhole.

In the embodiment of Fig. 1, the tool 22 includes an optical interface 34 coupled to the optical fiber(s) 20, and a sensor 36 coupled to the optical interface 34. The sensor 36 is

intended to be a generic sensor that represents a variety of sensing equipment that may be used in a wide array of different tools. The sensor 36 produces an electrical signal in response to a particular measurement (e.g., magnetic field changes attributable to passing casing collars in case the tool 22 is a CCL).

The optical interface 34 of the tool 22 may include a light source controlled or modulated by the electrical signal received from the sensor 36, thereby producing an optical signal. The light source may include, for example, an incandescent lamp, an arc lamp, an LED, a laser, an amplified spontaneous emission source, or a super-luminescent diode. The optical interface 34 transmits an optical signal to the surface equipment 28 via the optical fiber(s) 20 of the cable 18. The surface equipment 28 processes the optical signal received via the optical fiber(s) 20 to reconstruct the original data signal generated by the tool 22.

In at least some embodiments, the surface equipment 28 includes a photodetector that receives the optical signal and converts it into an electrical signal (e.g., a voltage or a current) dependent on one or more characteristics of the optical signal. The photodetector may be or include, for example, a photodiode, a photoresistor, a charge-coupled device, or a photomultiplier tube. In some embodiments, the light source of the tool 22, described above, may instead be positioned within or in communication with the surface equipment 28. In such embodiments, even though the light source is located at the surface, the downhole equipment may modulate the light that illuminates the optical fiber(s) 20. In at least some embodiments, light that illuminates the optical fiber(s) 20—regardless of the location of the light source that generates that light—is of a fixed wavelength, meaning that the wavelength of that light is constant or varies by no more than 5% in either direction from a baseline wavelength. In some embodiments, only one light source illuminates the optical fiber(s) of the cable 18. The contents of the surface equipment 28 are described in greater detail below.

In the embodiment of Fig. 1, the cable 18 preferably also includes armor to add mechanical strength and/or to protect the cable from shearing and abrasion. Some of the optical fiber(s) 20 may be used for power transmission, communication with other tools, and redundancy. The cable 18 may, in some cases, also include electrical conductors if desired. The cable 18 spools to and from a winch 42 as the sonde 12 is conveyed through the casing string 16. The reserve portion of the cable 18 is wound around a drum of the winch 42, and the cable 18 having been dispensed or unspooled from the drum supports the sonde 12 as it is conveyed through the casing string 16.

In the illustrated embodiment, the winch 42 includes an optical slip ring 44 that enables the drum of the winch 42 to rotate while making an optical connection between the

optical fiber(s) 20 and corresponding fixed port(s) of the slip ring 44. The surface equipment 28 is connected to the port(s) of the slip ring 44 to send and/or receive optical signals via the optical fiber(s) 20. In other embodiments, the winch 42 includes an electrical slip ring 44 to send and/or receive electrical signals from the surface equipment 28 and an electro-optical interface that translates the signals from the optical fiber 20 for communication via the slip ring 44 and vice versa.

Figure 2A is a conceptual block diagram of an optical telemetry system 200. The system 200 includes a light source 202, a polarization controller 204, a downlink modulator 206, a receiver 208, and a circulator 210 (which, in some embodiments, is located immediately before the slip ring 44), all of which may collectively be considered as "surface equipment" and may be housed within and/or coupled to, e.g., the surface equipment 28 depicted in Figure 1. The system 200 also includes a coupler 214 (e.g., a 1x3 coupler), a receiver 216 and an uplink modulator 218, all of which may collectively be considered as "downhole equipment" and may be housed within and/or coupled to, e.g., the sonde 12 depicted in Figure 1. The surface equipment and downhole equipment communicate via fiber channel 212 (i.e., within a fiber optic cable). As the shading in Figure 2A indicates, blocks 202, 204, 206, 210, 214 and 216 are used to transmit data in a downlink session—i.e., transmit data from the surface equipment to downhole equipment. Figure 2B, which also depicts system 200 and is described below, depicts blocks 202, 204, 208, 210, 214 and 218 being used to transmit data in an uplink session—i.e., transmit data from the downhole equipment to surface equipment.

The light source 202 may be any suitable type of light source, including a laser, light emitting diode, super-luminescent diode, or amplified spontaneous emission source. In some embodiments, the light source 202 operates at wavelengths between 400 nm and 2500 nm. In some embodiments, the light source 202 operates with coherence lengths between 1 micron and 2000 km. The polarization controller 204 adjusts the polarization of the light output by the light source 202 for optimal use. (If the light source 202 is depolarized, the polarization controller 204 is unnecessary. Further, in some embodiments, a polarization scrambler may be used in lieu of the polarization controller 204.) The polarization controller 204 may adjust polarization manually or electronically and may use fiber strain, compression, torsion and/or temperature techniques. Oher optical devices may be used to condition the light, such as optical filters, optical isolators, optical decoherers, optical amplifiers, optical attenuators, and the like. In at least some embodiments, the light output by the light source 202 has a fixed wavelength. A "fixed wavelength" may mean either a constant wavelength with no variation or a wavelength that varies no more than 5% in either direction from a baseline wavelength. In at

least some embodiments, the light source 202 is the only light source that illuminates the fiber channel 212, and in some such embodiments, the light source 202 is positioned downhole instead of at the surface. In some embodiments, multiple light sources may be used to illuminate the fiber channel 212 (e.g., one light source at the surface and another light source downhole; two light sources at the surface). All such variations are contemplated and included within the scope of disclosure.

The downlink modulator 206 modulates the light output by the polarization controller 204 to include the data to be transmitted downhole (i.e., in a "downlink" session). Any suitable modulation technique may be used. For example, in some embodiments, the modulator 206 modulates the intensity (i.e., amplitude) of the light according to an analog signal to be transmitted downhole. In some embodiments, the modulator 206 modulates the light using pulse frequency modulation based on a digital signal to be transmitted downhole. In still other embodiments, the modulator 206 modulates the light using phase modulation based on a digital signal to be transmitted downhole. Other modulation techniques also are contemplated. In some embodiments, the modulator 206 comprises an electro-optic modulator, an electro-absorption modulator, a semiconductor optical amplifier, an optical switch, a ring resonator, or a fiber attenuator. In some embodiments, the modulator 206 operates on light having wavelengths between 400 nm and 2500 nm. In some embodiments, the modulator 206 modulates from 1 Hz to 100 GHz. The modulator 206 may maintain polarization or be polarization insensitive. The modulator 206 may also modulate the polarization to convey data through altered polarization states. In some embodiments, the modulator 206 must be maintained at maximum power output while the system is in uplink mode (e.g., as shown in Figure 2B).

The circulator 210 directs light from the modulator 206 to the fiber channel 212 and from the fiber channel 212 into the receiver 208 (the latter in case of uplink sessions, as shown in Figure 2B, or as a reliability monitor in case of downlink sessions). The fiber channel 212 passes light between the surface and downhole equipment. In some embodiments, the length of the fiber channel 212 is up to 18 km. In some embodiments, the fiber channel 212 comprises pure silica or is doped with erbium, ytterbium, neodymium, quantum dots, nanoparticles, and/or boron. The fiber channel 212 may be single mode, multi-mode, or polarization-maintaining. The fiber channel 212 may be jacketed with polyimide, silicone-perfluoroalkoxy, other polymers, a metal, or carbon composite. The fiber channel 212 is housed within a larger, composite fiber optic cable (e.g., cable 18 in Figure 1) that can include electrically conducting lines, other optical fibers, and/or structural support.

The coupler 214 splits the light from a single fiber channel 212 into multiple channels. In Figure 2A, the coupler 214 is depicted as being a 1x3 coupler that divides the light from the fiber channel 212 into three channels, although the scope of disclosure is not limited as such. One of the channels couples to the downlink receiver 216, and the other two channels couple to the uplink modulator 218. The coupler 214 also recombines the three channels into the single fiber channel 212. In some embodiments, the coupler 214 comprises pure silica or is doped with erbium, ytterbium, neodymium, quantum dots, nanoparticles, and/or boron. In some embodiments, the coupler 214 is single-mode, multi-mode or polarization-maintaining. In some embodiments, the coupler 214 is jacketed with polyimide, silicone-perfluoroalkoxy, other polymers, a metal, or carbon composite.

The downlink receiver 216 converts optical power to voltage for processing. In some embodiments, the receiver 216 operates to 300 degrees Celsius. In some embodiments, the receiver 216 comprises a photodiode, a photomultiplier tube or a thermopile. In some embodiments, the receiver 216 operates on light having a wavelength between 400 nm and 2500 nm. In some embodiments, the receiver 216 detects signals between 1 Hz and 100 GHz. In some embodiments, the receiver 216 has a sensitivity between 0 dBm and -80 dBm.

In some embodiments, the circulator 210 may be configured to provide a downlink signal from the downlink modulator 206 to the 1x3 coupler 214 and, in addition, the same downlink signal may be provided to the surface receiver 208. (In at least some such embodiments, the circulator 210 may be replaced by any other suitable type of hardware that can perform this specific routing function.) By providing a copy of the downlink signal to the surface receiver 208, the quality of the downlink signal can be verified and any problems with the downlink signal can be corrected.

As alluded above, Figure 2B shows the same system 200 as Figure 2A, but it highlights those components that are used to communicate data in an uplink session—i.e., from downhole equipment to surface equipment. Specifically, the light source 202 and polarization controller 204 are still used to help illuminate the fiber channel 212. However, the downlink modulator 206 is not used to modulate downlink data, and the downlink receiver 216 is not used to receive downlink data. Instead, as depicted by the shaded components in Figure 2B, during an uplink session the uplink modulator 218 is used to modulate light illuminating the fiber channel 212 and the uplink receiver 208 is used to receive data from the fiber channel 212. The uplink modulator 218 and uplink receiver 208 are inactive in the system of Figure 2A.

The uplink modulator 218 may modulate light in the same or substantially similar way as the downlink modulator 206. The uplink receiver 208 may receive and process light in the same or substantially similar way as the downlink receiver 216. In some embodiments, the uplink receiver 208 has a sensitivity between 0 dBm and -80 dBm and can be cooled using Peltier coolers, heat sinks, heat fins, or cryocoolers.

In some embodiments, the coupler 214 may be configured to provide an uplink signal from the uplink modulator 218 to the circulator 210 and, in addition, the same uplink signal may be provided to the downlink receiver 216. (In at least some such embodiments, the coupler 214 may be replaced by any other suitable type of hardware that can perform this specific routing function.) By providing a copy of the uplink signal to the downlink receiver 216, the quality of the uplink signal can be verified and any problems with the uplink signal can be corrected.

Figure 3 is a block diagram of an illustrative optical telemetry system and is a more detailed depiction of the system shown in Figure 2. Specifically, a portion 301 of a tool (e.g., a CCL coil) couples to an amplifier 300. The output of the amplifier 300 is provided to analog-to-digital converter (ADC) 306 via connection 308. The ADC 306 forms part of a processor 302, which couples to a memory 304 (e.g., volatile or permanent memory) and further comprises an input/output (I/O) port 314. A switch 312 couples to the I/O port 314 and the amplifier 300 via connections 316 and 310, respectively. The output of the switch 312 couples to a modulator 318, the output of which couples to a coupler 322 via connection 320. The coupler 322 couples to the modulator 318 via connection 353 and to photodiode 352 via connection 351. The photodiode 352, in turn, couples to a transimpedance amplifier 354, and the amplifier 354 couples to an ADC 356. The ADC 356 couples to the processor 302. In at least some embodiments, the components 300, 302, 304, 306, 312, 314, 318, 322, 352, 354 and 356 form some or all of the optical interface 34 (Fig. 1).

The coupler 322 couples to circulator 324 (at the surface) via a fiber optic cable 323. Circulator 324 couples to photodiode 326 via connection 325, and the photodiode 326 couples to a transimpedance amplifier 328. The amplifier 328, in turn, couples to an ADC 334 via connection 330 and to an I/O port 336 via connection 332. The port 336 and ADC 334 form part of a processor 338, which couples to a surface computer 342 via connection 340 and to a modulator 348 via connection 346 that is driven by a light source (e.g., a laser) 344. The modulator 348 couples to the circulator 324 via connection 350. In some embodiments, at least connections 350, 323, 353, 320, 351, and 325 are fiber optic cable connections.

In operation, the signal from the portion 301 of the downhole tool is amplified by the amplifier 300, and the amplified signal is provided to ADC 306 and to the switch 312. The signal that is provided directly to the switch 312 via the connection 310 is an analog signal. The signal provided to the ADC 306 is also analog but is digitized and the processor 302 subsequently generates a spectrum-shifted, pulse frequency modulated signal at the I/O port 314. The analog signal on connection 310 and the digital signal on connection 316 are provided to switch 312. The switch 312 is preferably controlled by the processor 302. The switch 312 permits either the analog signal or the digital signal to pass to the modulator 318. The modulator 318 receives light from light source 344 on the connection 353. The modulator 318 modulates the light within the fiber optic cable 353 using any suitable modulation technique. For example, in some embodiments, the modulator 318 modulates the intensity (i.e., amplitude) of the light according to the analog signal received on connection 310. In some embodiments, the modulator 318 modulates the light using pulse frequency modulation based on the digital signal received on the connection 316. In still other embodiments, the modulator 318 modulates the light using phase modulation based on the digital signal received on the connection 316. Other modulation techniques also are contemplated.

The modulated optical signal is provided to the coupler 322 via connection 320. The coupler 322 routes the modulated optical signal to the surface via the fiber optic cable 323. The circulator 324 routes the modulated optical signal to the photodiode 326, which converts the modulated optical signal to an electrical signal that is amplified by the amplifier 328. The resulting analog or digital signal is provided to the ADC 334 or the I/O port 336, as appropriate. The processor 338 then processes the resulting signal to reconstruct the original signal and provides the reconstructed signal to a surface computer 342 to be used as desired. In this way, signals are periodically or continuously communicated from the downhole to the surface computer 342.

The aforementioned spectrum-shifted, pulse frequency encoding and modulation of the digitized signal may be performed in any suitable manner. In at least some embodiments, the encoding and modulation are performed as follows. First, the amplitude of the analog to be digitized is determined. The amplitude is assigned to one of a plurality of digital values. The number of possible digital values depends at least in part on the number of bits used to encode the digitized signal. For example, for an 8-bit signal, there are 256 possible digital values, and each of these values is assigned to a different pulse frequency (shifted by a predetermined amount, e.g., 100 kHz). Thus, for instance, 100 kHz could represent the 8-bit signal "00000000," while 355 kHz could represent the 8-bit signal "11111111." A data structure

containing the digital value-to-pulse frequency mapping is accessible to both processors 302, 338. To reconstruct the modulated signal, the processor 338 determines the pulse frequency of the optical signal and uses its data structure to determine the original analog signal. Phase-modulated and amplitude-modulated signals may be similarly reconstructed.

In at least some embodiments, the aforementioned optical signal in the fiber optic cable is generated by a single light source 344 (e.g., a laser source) at the surface. In such embodiments, there are no other light sources illuminating the fiber optic cable. In some embodiments, the single light source may be located downhole—for example, in the sonde, and in such embodiments, there are no other light sources illuminating the fiber optic cable. In either case, the light generated by the light source preferably has a fixed wavelength, which is what gives rise to the need for only a single light source. The wavelength is "fixed" in the sense that it either does not vary or only varies within a small, predetermined range—in at least some embodiments, within +/- 5% of the original, baseline wavelength used during a particular telemetry session. The specific wavelength used may be selected as desired and as may be suitable. The light generated by the light source 344 is provided to modulator 348, which modulates the light with data signals that are to be transmitted downhole. Such data signals are generated by the processor 338 and/or by the surface computer 342 and are provided to the modulator 348 via connection 346. The modulator 348 may use any suitable modulation technique, such as intensity (i.e., amplitude) modulation, phase modulation and/or pulse-frequency modulation, as described above. Other modulation techniques are contemplated.

The modulated signal is provided to the circulator 324 via connection 350. The circulator 324 directs light from the modulator 348 to the fiber optic cable 323. The coupler 322 splits the single optical channel in the fiber optic cable 323 into three separate channels (i.e., on connections 351, 320, 353). The coupler 322 routes the incoming signal to the photodiode 352, where the modulated optical signal is converted into an electrical signal that is amplified by the transimpedance amplifier 354 and converted to digital format by ADC 356. The digital signal is then provided to the processor 302 to be used as desired.

As explained above, Figures 2A-2B depict a general optical telemetry system, and Figure 3 is a more detailed depiction of the systems in Figures 2A-2B. Figures 4-11, described below, are alternative versions of the systems in Figures 2A-2B. Accordingly, the system shown in Figure 3 may be modified as necessary and as may be suitable to adapt to the various embodiments of Figures 4-11 (e.g., by adding, removing or modifying components). In at least some embodiments, the systems depicted in Figures 4-11 contain light sources that generate fixed-wavelength light.

Figure 4 is a block diagram of another illustrative optical telemetry system and is an alternative to the systems shown in Figures 2A-2B. Figure 4 shows a system 400 that includes many of the same components as the systems 200 of Figures 2A-2B. These components include the light source 202, the polarization controller 204, the downlink modulator 206, the receiver 208, the circulator 210, the fiber channel 212, the receiver 216 and the uplink modulator 218. The system 400 includes additional components not shown in the systems 200 of Figure 2A-2B. Specifically, the system 400 includes a circulator 402 and a coupler 404 (e.g., a 1x2 coupler). The circulator 402 is used to ensure that the light in the fiber optic channel passing through the uplink modulator 218 only passes in one direction through the modulator 218 (i.e., from the coupler 404, through the modulator 218 and back to the circulator 402) when the system 400 is operating in an uplink telemetry mode. The 1x3 coupler 214 of Figures 2A-2B is replaced in Figure 4 by the 1x2 coupler 404.

Figure 5 is a block diagram of another illustrative optical telemetry system and is an alternative to the systems shown in Figures 2A-2B. The system 500 depicted in Figure 5 is similar to those shown in Figures 2A-2B in that it contains the light source 202, polarization controller 204, downlink modulator 206, receiver 208, circulator 210, fiber channel 212, coupler 214 (e.g., a 1x3 coupler), receiver 216 and uplink modulator 218. The system 500 differs from the systems 200 of Figures 2A-2B in that the system 500 further includes an uplink isolator 502. The isolator 502 ensures that light travels in only one direction through the modulator 218 when the system 500 is operating in an uplink telemetry mode (e.g., from coupler 214 to isolator 502, and from isolator 502 to modulator 218, and from modulator 218 to the coupler 214). The isolator 502 reduces inter-symbol interference of uplink data at high data rates.

Figure 6 is a block diagram of another illustrative optical telemetry system and is another alternative to the systems shown in Figures 2A-2B. The system 600 depicted in Figure 6 is similar to those shown in Figures 2A-2B in that it contains the light source 202, polarization controller 204, downlink modulator 206, receiver 208, fiber channel 212, coupler 214 (e.g., a 1x3 coupler), receiver 216, and uplink modulator 218. The system 600 differs from the systems 200 of Figures 2A-2B in that the system 600 further includes an isolator 602 and a coupler 604 (e.g., a 1x2 coupler). By using the isolator 602 and the coupler 604, the wavelength of the light source may be altered without significant reduction in telemetry quality (compared to the use of a circulator).

Figure 7 is a block diagram of another illustrative optical telemetry system and is another alternative to the systems shown in Figures 2A-2B. The system 700 depicted in Figure

7 is similar to those shown in Figures 2A-2B in that it contains the light source 202, polarization controller 204, downlink modulator 206, receiver 208, circulator 210, fiber channel 212, receiver 216 and uplink modulator 218. The system 700 differs from the systems 200 of Figures 2A-2B in that the system 700 further includes a coupler 702 (e.g., a 1x2 coupler) and a coupler 704 (e.g., a 1x2 coupler). The 1x2 couplers, such as couplers 702 and 704, can operate at high temperatures and are commercially available in high volumes at low costs. Thus, using the system 700 instead of the systems 200 depicted in Figures 2A-2B may enhance cost efficiencies.

Figure 8 is a block diagram of another illustrative optical telemetry system and is another alternative to the systems shown in Figures 2A-2B. The system 800 depicted in Figure 8 is similar to those shown in Figures 2A-2B in that it contains the light source 202, polarization controller 204, modulator 206, receiver 208, fiber channel 212, receiver 216 and uplink modulator 218. The system 800 differs from the systems 200 of Figures 2A-2B in that the system 800 further includes a coupler 802 (e.g., a 1x2 coupler), a coupler 804 (e.g., a 1x2 coupler), and a fiber mirror 806. In at least some embodiments, the fiber mirror 806 comprises a Faraday rotator mirror. In at least some embodiments, the fiber mirror 806 comprises a chemically coated fiber tip. The coated fiber tip may be coated with aluminum, silver or gold with reflectivities of over 95%, 97.5%, and 99%, respectively, at 1 micrometer and above. The fibers may be coated using evaporation, sputtering or chemical processes (such as Brashear's Method or Böttger's Rochelle Salt Method). By using one or more of the 1x2 couplers as shown and by including the fiber mirror 806, the power delivered to both the downlink and uplink receivers 216, 208 can be increased. Further, by passing the light twice through the uplink modulator 218, voltage changes on the uplink data may be reduced while still obtaining the same signal modulation depth. The mirror 806 provides a command protocol enhancement by echoing data from the surface back to the surface for confirmation. The mirror 806 also provides a hardware confirmation for the test setup without having to feed data into the downhole modulator 218. By transmitting data through the surface modulator 206, the hardware in the downlink data path (206, 802, 212, 804, 216) and uplink data path (806, 218, 804, 212, 802, 208) can be verified to ensure they are operational and functional, and the mirror 806 acts as a quality indicator for the fiber connections by comparing the original data signal sent uphole and the resultant signal at the surface receiver 208.

Figure 9 is a block diagram of another illustrative optical telemetry system and is another alternative to the systems shown in Figures 2A-2B. The system 900 depicted in Figure 9 is similar to those shown in Figures 2A-2B in that it contains the receiver 208, circulator 210,

the fiber channel 212, the coupler 214, the receiver 216, and the uplink modulator 218. The system 900 differs from the systems 200 of Figures 2A-2B in that the system 900 further includes a directly-driven light source 902. In lieu of generating light and subsequently modulating it as is done in the systems 200 of Figures 2A-2B, the directly-driven light source 902 directly modulates the light as the light is generated. This is accomplished by manipulating the current passing through the light source 902—for example, using a switch. By rapidly switching the current on and off or by adjusting the current in an analog fashion, data can be modulated directly using the light source. This technique is more cost effective and robust than separately generating and modulating light, and it also reduces the polarization sensitivity of the system as polarization compatibility between the light source and the downlink modulator has been removed. As with the light source 202, the directly-driven light source 902 produces fixed-wavelength light.

Figure 10A is a block diagram of another illustrative optical telemetry system and is another alternative to the systems shown in Figures 2A-2B. The system 1000 depicted in Figure 10A is similar to those shown in Figures 2A-2B in that it contains the light source 202, downlink modulator 206, receiver 208, circulator 210, fiber channel 212, coupler 214 (e.g., a 1x3 coupler), receiver 216 and uplink modulator 218. The system 1000 differs from the systems 200 of Figures 2A-2B in that the system 1000 further includes a depolarizer 1002 coupled between the light source 202 and the downlink modulator 206 and a polarization controller 1004 coupled between the downlink modulator 206 and the circulator 210. The positioning of the polarization controller 1004 and the downlink modulator 206 relative to the other components as shown in Figure 10A is advantageous because it mitigates polarization drift that could occur if the light that enters the downlink modulator 206 were polarized. However, by depolarizing the light before it enters the modulator 206, at least 50% of the light will be aligned with the polarizer that is typically internal to modulators such as modulator 206. In addition, by controlling polarization of the light after the light passes through the modulator 206 (e.g., using the polarization controller 1004), the light that will be modulated by the uplink modulator 218 can be polarized to match the polar orientation of the polarizer that is internal to the uplink modulator 218.

Similar mitigation of polarization drift may be achieved using the embodiments shown in Figures 10B and 10C. Specifically, Figure 10B shows a system 1020 that includes several of the components depicted in Figures 2A-2B, including the downlink modulator 206, receiver 208, circulator 210, fiber channel 212, coupler 214 (e.g., 1x3 coupler), receiver 216, and uplink modulator 218. The system 1020 further includes a depolarized light source 1022 positioned

upstream of the downlink modulator 206, and a polarization controller 1024 positioned between the downlink modulator 206 and the circulator 210. The depolarized light source 1022 and the polarization controller 1024, having the specific positions shown in Figure 10B, achieve the same or similar anti-polarization drift effect as the depolarizer 1002 and the polarization controller 1004 in Figure 10A. As explained above, in at least some embodiments, a polarization scrambler may be used in lieu of a depolarization controller.

Similarly, Figure 10C shows a system 1040 that includes several components shown in Figures 2A-2B, including the light source 202, polarization controller 204, downlink modulator 206, receiver 208, circulator 210, fiber channel 212, coupler 214 (e.g., a 1x3 coupler), receiver 216, and uplink modulator 218. The system 1040 further includes a polarization controller 1042 between the downlink modulator 206 and the circulator 210. This specific positioning of the polarization controller 1042 achieves the same or similar anti-polarization drift effect as that achieved in the systems of Figures 10A-10B.

Figure 11 is a block diagram of another illustrative optical telemetry system and is another alternative to the systems shown in Figures 2A-2B. The system 1100 contains several of the components shown in Figures 2A-2B, including the light source 202, polarization controller 204, downlink modulator 206, receiver 208, circulator 210, fiber channel 212, coupler 214 (e.g., a 1x3 coupler), receiver 216 and uplink modulator 218. The system 1100 additionally includes an amplifier 1102 to amplify the signal received at the receiver 208. In some embodiments, the amplifier 1102 is repositioned to another location within the system 1100 to amplify optical signal(s) as necessary. In some embodiments, more than one amplifier is used in the system 1100 to amplify optical signal(s) as necessary.

Each of the systems described herein, in at least some embodiments, operates using a modified half-duplex telemetry scheme. To facilitate an explanation of such a scheme, the fiber optic channel between the surface and downhole equipment in each of these systems may be modeled as a single, continuous channel that runs from the light source on one end (at either the surface or downhole), to the other end (either the downhole or the surface), and back to the light source again. Thus, for instance, if an embodiment has a single light source positioned at the surface, the optic channel may be modeled as a single channel extending from the light source downhole, to the downhole modulator, and back up to the light source at the surface.

Bearing in mind such a model, it is evident that modulation that occurs at any given point along the optical channel will interfere with any additional modulation that occurs downstream of that modulation, but it is also evident that any such downstream modulation will not interfere with any modulation that occurs upstream from that point. For instance, in

the system 200 of Figures 2A-2B, the downlink modulator 206 is upstream of the uplink modulator 218 (i.e., light from the light source 202 passes through the downlink modulator 206 before it passes through the uplink modulator 218). Thus, any modulation applied to the light at the downlink modulator 206 is going to interfere with modulation attempts at the uplink modulator 218. However, modulation at the uplink modulator 218 will not interfere with modulation attempts at the downlink modulator 206. Accordingly, the uplink modulator 218 is said to give deference to the downlink modulator 206, and the downlink modulator 206 is said to have priority over the uplink modulator 218. Thus, the telemetry in systems 200 may be monitored using any of a variety of well-known techniques to ensure that uplink sessions only occur when the downlink modulator 206 is not modulating the light. However, no such restriction is necessary during downlink sessions, meaning that downlink sessions can occur irrespective of whether the uplink modulator 218 is modulating the light (since any uplink modulation occurs at the modulator 218 and does not interfere with downlink telemetry). However, the latter situation should be avoided if possible so that the uplink modulator 218 can complete its telemetry session without impediment.

Figure 12 is a flow diagram of a method 1200 to communicate data using one or more of the optical telemetry systems described herein. The method 1200 begins with obtaining a data signal to transmit in an uplink or downlink telemetry session (step 1202). Such data may be obtained, for instance, from a downhole tool (e.g., a CCL) or it may be data that must be transmitted from the surface to downhole equipment. The scope of disclosure is not limited to the transmission of any particular type of data. The method 1200 next includes using a single light source to illuminate an optical fiber channel with fixed-wavelength light (step 1204). As explained, this single light source may take any suitable form and may be positioned at the surface or downhole. The scope of disclosure, however, is not limited to embodiments having a single light source, and in some embodiments, multiple light sources may be used. The method 1200 next includes modulating the fixed-wavelength light to carry the data signal using a modified half-duplex telemetry scheme (step 1206). The modulated light is then received at the surface equipment or at the downhole equipment (step 1208), and the modulated light is demodulated to recover the original data signal (step 1210). Finally, the method 1200 comprises processing the original data signal as desired and appropriate (step 1212). The method 1200 may be modified in any suitable manner, including the addition, deletion or modification of the steps and/or the order in which they are performed.

Numerous other variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims

be interpreted to embrace all such variations, modifications and equivalents. In addition, the term "or" should be interpreted in an inclusive sense. Further, the term "couple," as used herein, implies a direct or indirect connection between two or more components.

In at least some embodiments, a system comprises: a light source; a fiber optic cable coupled to surface equipment and to downhole equipment and illuminated with fixed-wavelength light by said light source; and a modulator to modulate said fixed-wavelength light in the fiber optic cable to communicate data between the surface equipment and the downhole equipment, wherein the modulator uses a modified half-duplex telemetry scheme. Some such embodiments may be supplemented in various ways, including by one or more of the following concepts, in any order and in any combination: wherein the fiber optic cable is illuminated only by said light source; further comprising a circulator that directs said fixed-wavelength light from the modulator to the fiber optic cable and from the fiber optic cable to a receiver or coupler; further comprising a coupler that divides a single channel in the fiber optic cable into multiple separate channels; wherein at least two of the multiple separate channels couple to the modulator and at least one of said multiple separate channels couples to a receiver; wherein at least one of the multiple separate channels directs said fixed-wavelength light to another coupler, wherein said another coupler directs said fixed-wavelength light to and receives said fixed-wavelength light from said modulator; wherein at least one of the multiple separate channels directs said fixed-wavelength light to said modulator, and wherein said modulator directs said fixed-wavelength light to a mirror, and wherein said mirror directs said fixed-wavelength light back to said modulator; wherein said light source is positioned at the Earth's surface; wherein the downhole equipment includes a tool that determines a subterranean formation property and communicates data representing said property to the surface equipment using the modulator and fiber optic cable; wherein the light source is selected from the group consisting of: a laser, a light-emitting diode, and an amplified spontaneous emission source; further comprising an isolator that directs said fixed-wavelength light between a coupler and said modulator; wherein the isolator is positioned at the Earth's surface; further comprising an amplifier that directs said fixed-wavelength light to a receiver; further comprising a depolarizer coupled to the light source and to the modulator, and further comprising a polarization controller coupled to the modulator and to a circulator, said circulator directs said fixed-wavelength light to the fiber optic cable; wherein said light source is a depolarized light source, and further comprising a polarization controller that directs said fixed-wavelength light from said modulator to a circulator, said circulator directs said fixed-wavelength light to the fiber optic cable; further comprising a first polarization controller that provides said fixed-

wavelength light to said modulator, and further comprising a second polarization controller that receives said fixed-wavelength light from the modulator.

In at least some embodiments, a system comprises: a directly-driven light source to output modulated, fixed-wavelength light; and a fiber optic cable couplable to surface equipment and to downhole equipment and illuminated by said modulated, fixed-wavelength light, wherein the fiber optic cable carries said modulated light using a modified half-duplex telemetry scheme. Some such embodiments may be supplemented in various ways, including using the following concept: wherein the surface equipment comprises a circulator and a receiver, said circulator couples to the directly-driven light source and to the fiber optic cable, and wherein the downhole equipment comprises a coupler, another receiver and a modulator, said coupler couples to the fiber optic cable and to the receiver and the modulator.

In at least some embodiments, a method comprises: providing fixed-wavelength light into a fiber optic cable; using a downhole tool to detect a subterranean formation property; and modulating said fixed-wavelength light in accordance with a signal produced by the downhole tool. Some such embodiments may be supplemented in various ways, including using the following concept: wherein said providing and said modulating comprise using a directly-driven light source.

CLAIMS

WE CLAIM:

1. A system, comprising:

a light source;

a fiber optic cable coupled to surface equipment and to downhole equipment and illuminated with fixed-wavelength light by said light source; and

a modulator to modulate said fixed-wavelength light in the fiber optic cable to communicate data between the surface equipment and the downhole equipment,

wherein the modulator uses a modified half-duplex telemetry scheme.

2. The system of claim 1, wherein the fiber optic cable is illuminated only by said light source.

3. The system of claim 1, further comprising a circulator that directs said fixed-wavelength light from the modulator to the fiber optic cable and from the fiber optic cable to a receiver or coupler.

4. The system of claim 1, further comprising a coupler that divides a single channel in the fiber optic cable into multiple separate channels.

5. The system of claim 4, wherein at least two of the multiple separate channels couple to the modulator and at least one of said multiple separate channels couples to a receiver.

6. The system of claim 4, wherein at least one of the multiple separate channels directs said fixed-wavelength light to another coupler, wherein said another coupler directs said fixed-wavelength light to and receives said fixed-wavelength light from said modulator.

7. The system of claim 4, wherein at least one of the multiple separate channels directs said fixed-wavelength light to said modulator, and wherein said modulator directs said fixed-wavelength light to a mirror, and wherein said mirror directs said fixed-wavelength light back to said modulator.

8. The system of claim 1, wherein said light source is positioned at the Earth's surface.

9. The system of claim 1, wherein the downhole equipment includes a tool that determines a subterranean formation property and communicates data representing said property to the surface equipment using the modulator and fiber optic cable.

10. The system of claim 1, wherein the light source is selected from the group consisting of: a laser, a light-emitting diode, and an amplified spontaneous emission source.

11. The system of claim 1, further comprising an isolator that directs said fixed-wavelength light between a coupler and said modulator.

12. The system of claim 11, wherein the isolator is positioned at the Earth's surface.

13. The system of claim 1, further comprising an amplifier that directs said fixed-wavelength light to a receiver.

14. The systems of claims 1-13, further comprising a depolarizer coupled to the light source and to the modulator, and further comprising a polarization controller coupled to the modulator and to a circulator, said circulator directs said fixed-wavelength light to the fiber optic cable.

15. The systems of claims 1-13, wherein said light source is a depolarized light source, and further comprising a polarization controller that directs said fixed-wavelength light from said modulator to a circulator, said circulator directs said fixed-wavelength light to the fiber optic cable.

16. The systems of claims 1-13, further comprising a first polarization controller that provides said fixed-wavelength light to said modulator, and further comprising a second polarization controller that receives said fixed-wavelength light from the modulator.

17. A system, comprising:

a directly-driven light source to output modulated, fixed-wavelength light; and

a fiber optic cable couplable to surface equipment and to downhole equipment and illuminated by said modulated, fixed-wavelength light,

wherein the fiber optic cable carries said modulated light using a modified half-duplex telemetry scheme.

18. The system of claim 17, wherein the surface equipment comprises a circulator and a receiver, said circulator couples to the directly-driven light source and to the fiber optic cable, and wherein the downhole equipment comprises a coupler, another receiver and a modulator, said coupler couples to the fiber optic cable and to the receiver and the modulator.

19. A method, comprising:

providing fixed-wavelength light into a fiber optic cable;

using a downhole tool to detect a subterranean formation property; and

modulating said fixed-wavelength light in accordance with a signal produced by the downhole tool.

20. The method of claim 19, wherein said providing and said modulating comprise using a directly-driven light source.

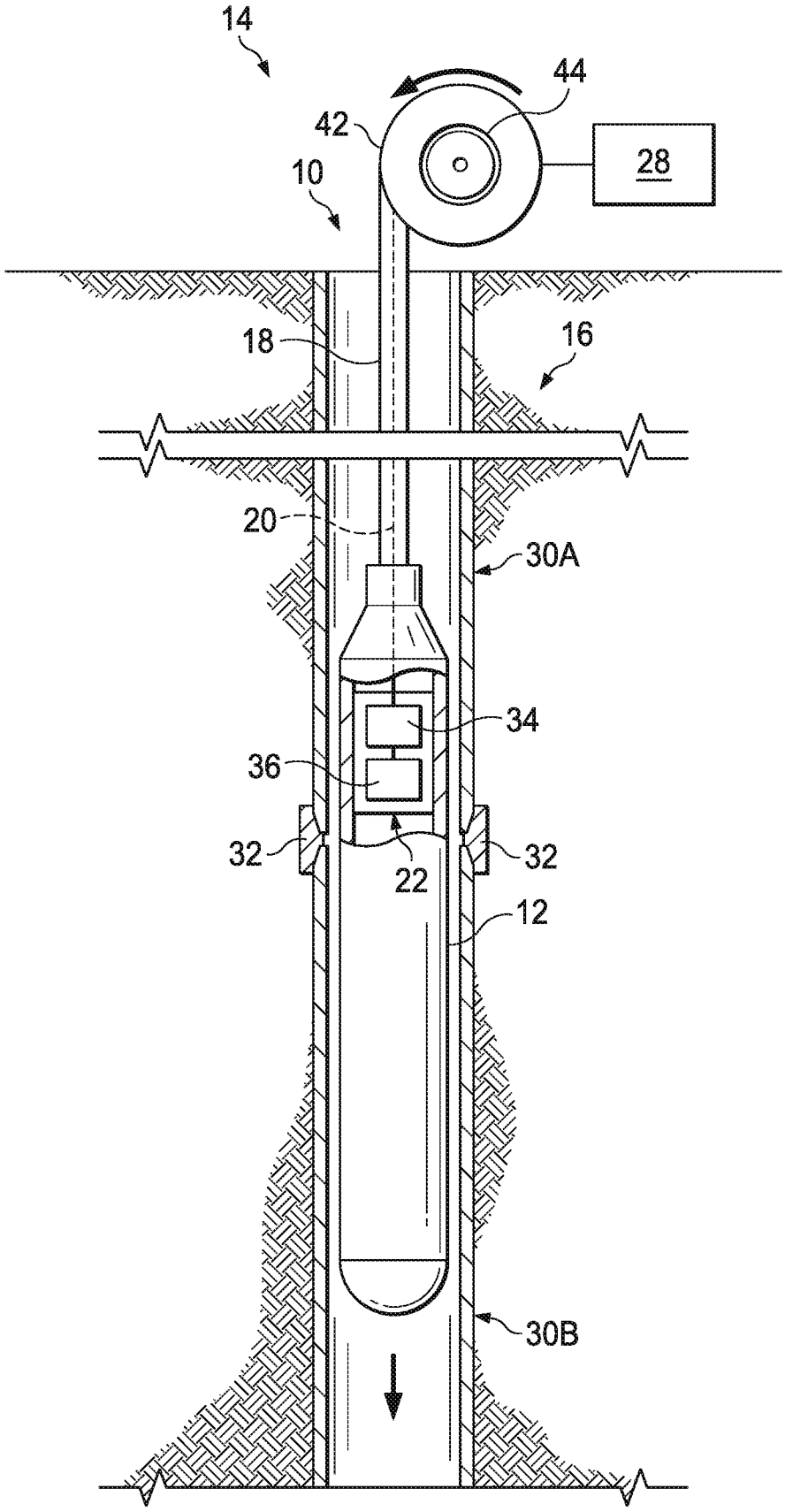


FIG. 1

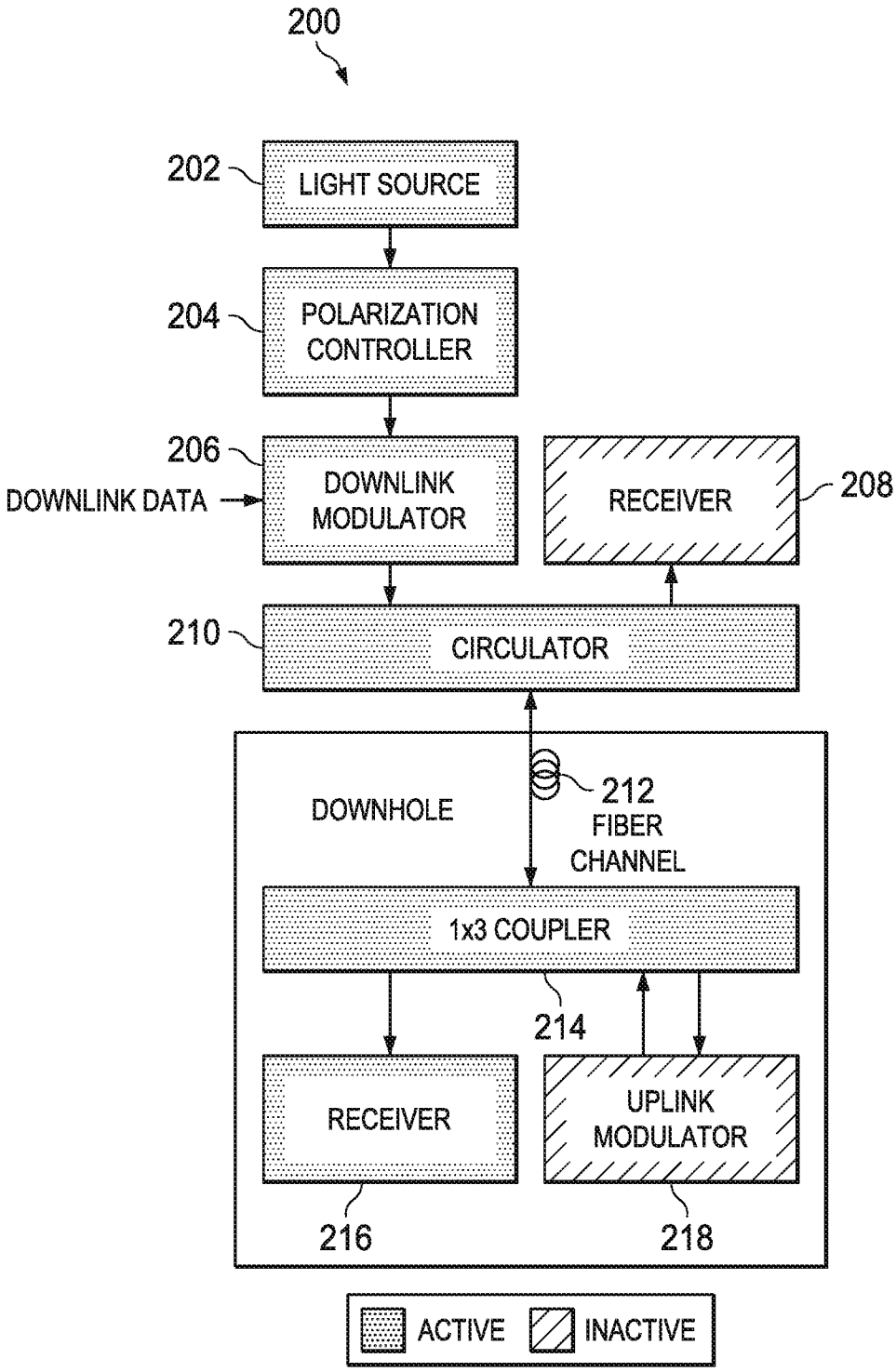

200
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
DOWNLINK DATA
DOWNLINK MODULATOR
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
UPLINK MODULATOR
216
218
ACTIVE
INACTIVE

FIG. 2A

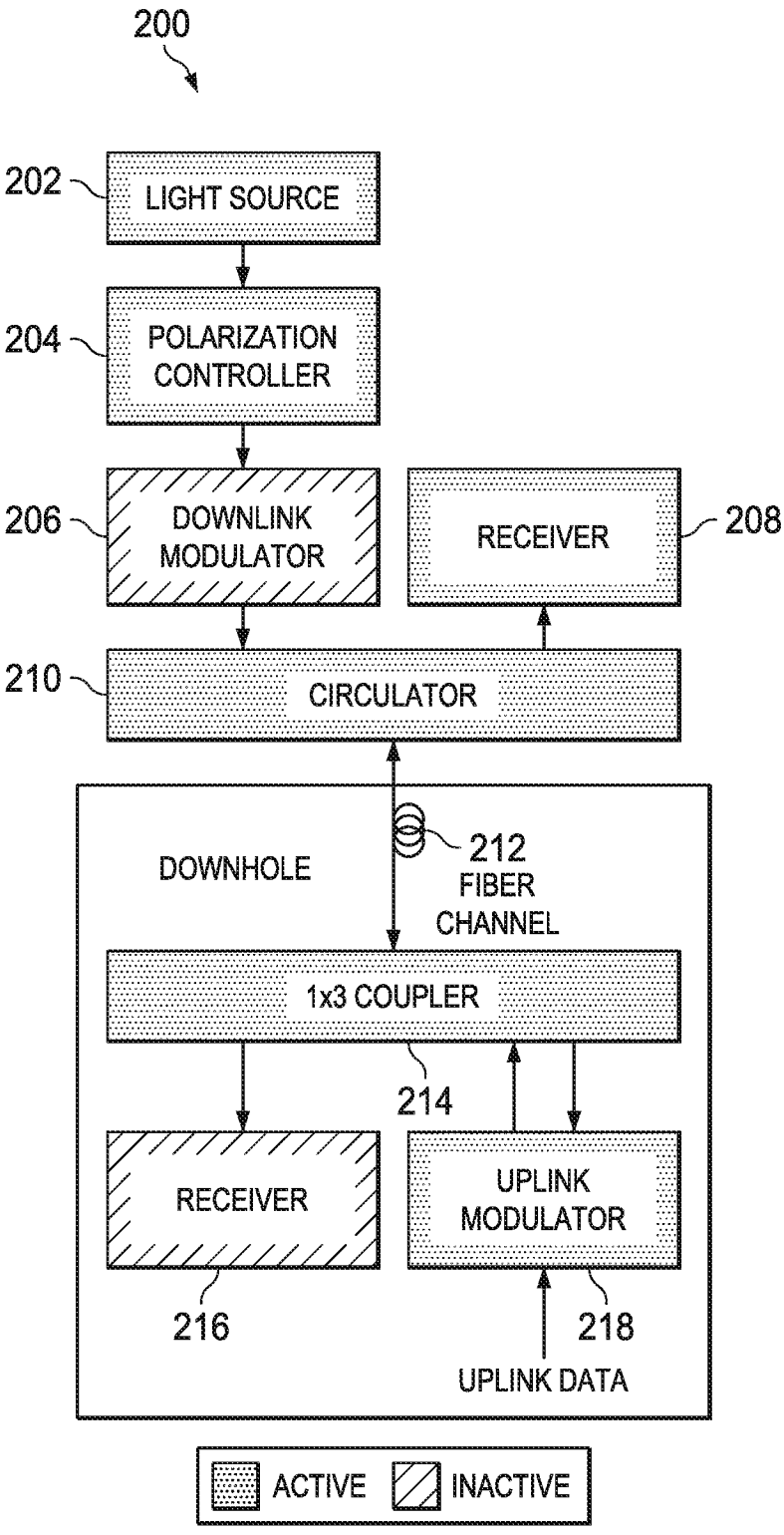

200
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
DOWNLINK MODULATOR
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
UPLINK MODULATOR
216
218
UPLINK DATA
ACTIVE
INACTIVE

FIG. 2B

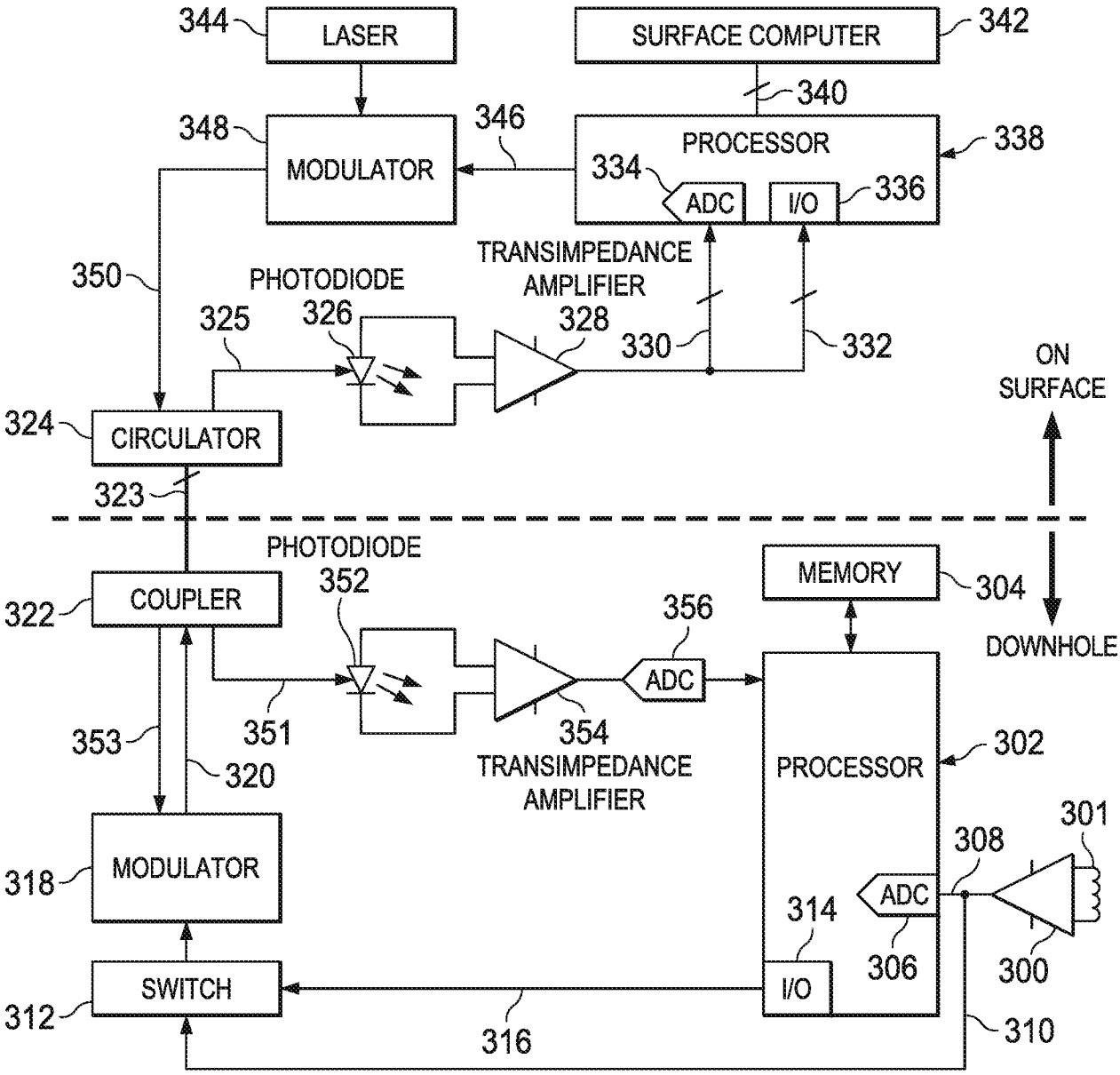

344
LASER
SURFACE COMPUTER
342
340
348
MODULATOR
346
PROCESSOR
338
334
ADC
I/O
336
TRANSIMPEDANCE
AMPLIFIER
350
PHOTODIODE
325
326
328
330
332
ON
SURFACE
324
CIRCULATOR
323
PHOTODIODE
352
MEMORY
304
322
COUPLER
356
ADC
DOWNHOLE
353
351
354
TRANSIMPEDANCE
AMPLIFIER
PROCESSOR
302
320
301
308
318
MODULATOR
ADC
314
306
300
SWITCH
I/O
312
316
310

FIG. 3

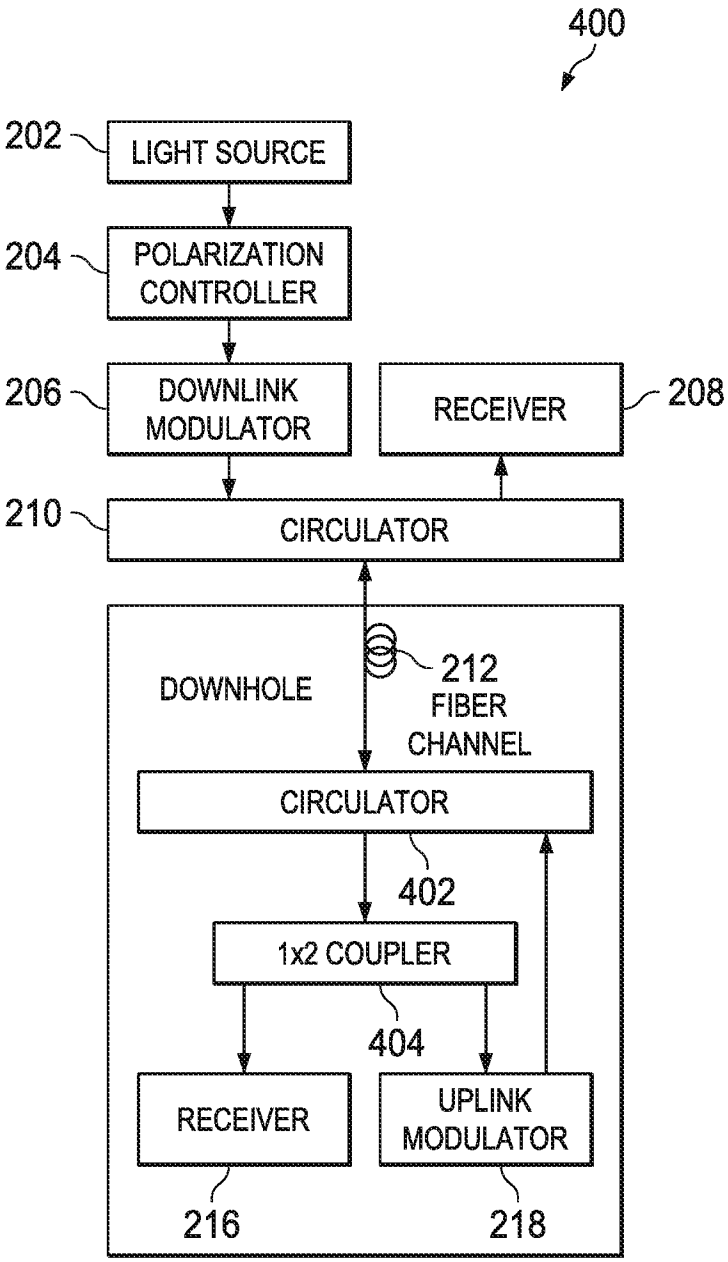

400
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
DOWNLINK MODULATOR
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
CIRCULATOR
402
1x2 COUPLER
404
RECEIVER
UPLINK MODULATOR
216
218

FIG. 4

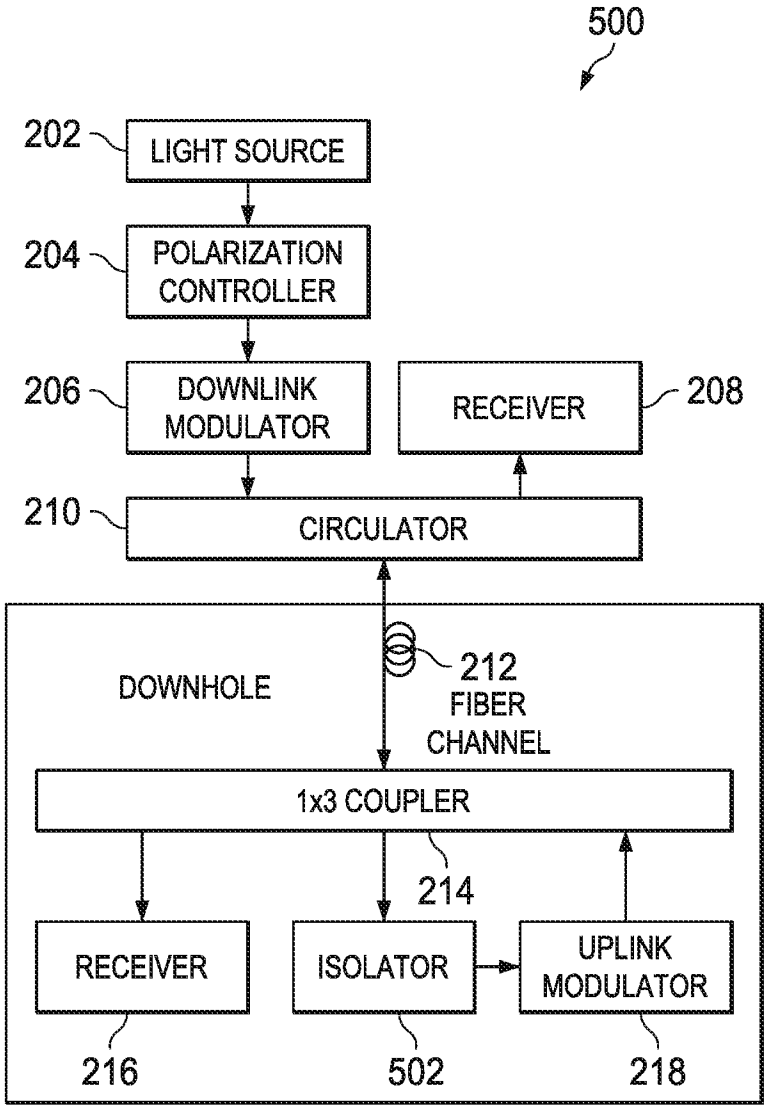

500
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
DOWNLINK MODULATOR
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
ISOLATOR
UPLINK MODULATOR
216
502
218

FIG. 5

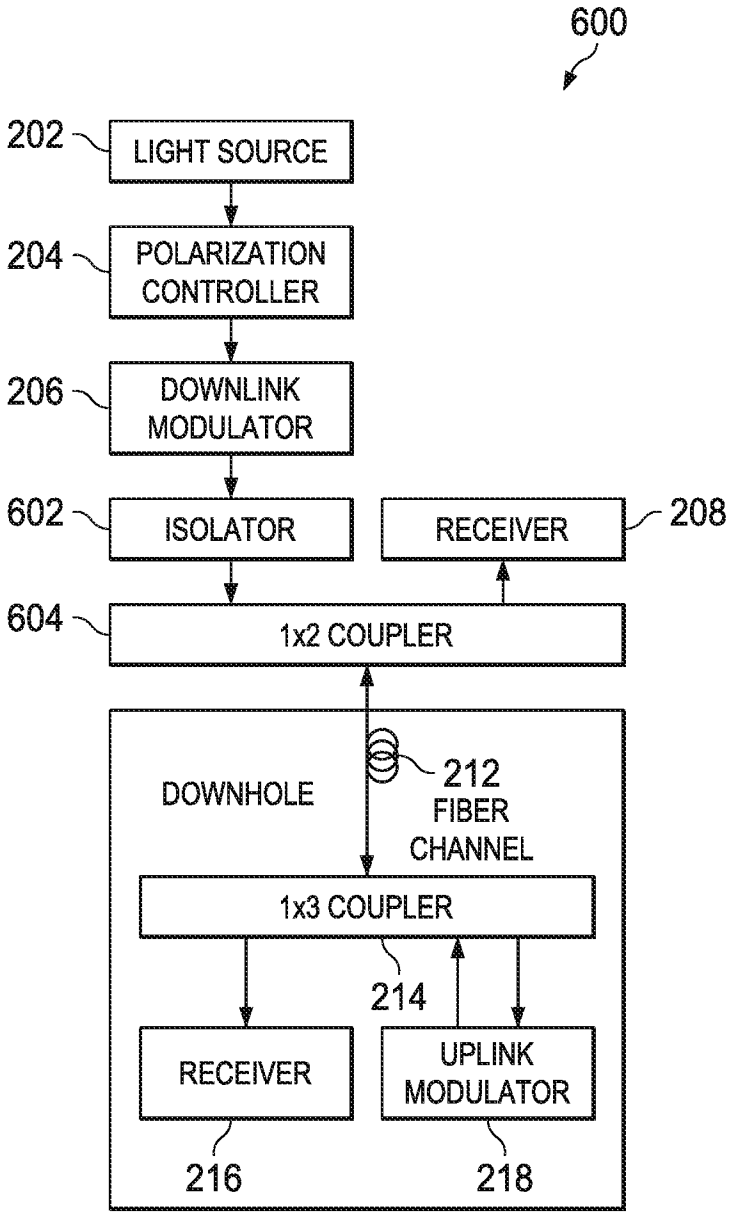

600
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
DOWNLINK MODULATOR
602
ISOLATOR
RECEIVER
208
604
1x2 COUPLER
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
UPLINK MODULATOR
216
218

FIG. 6

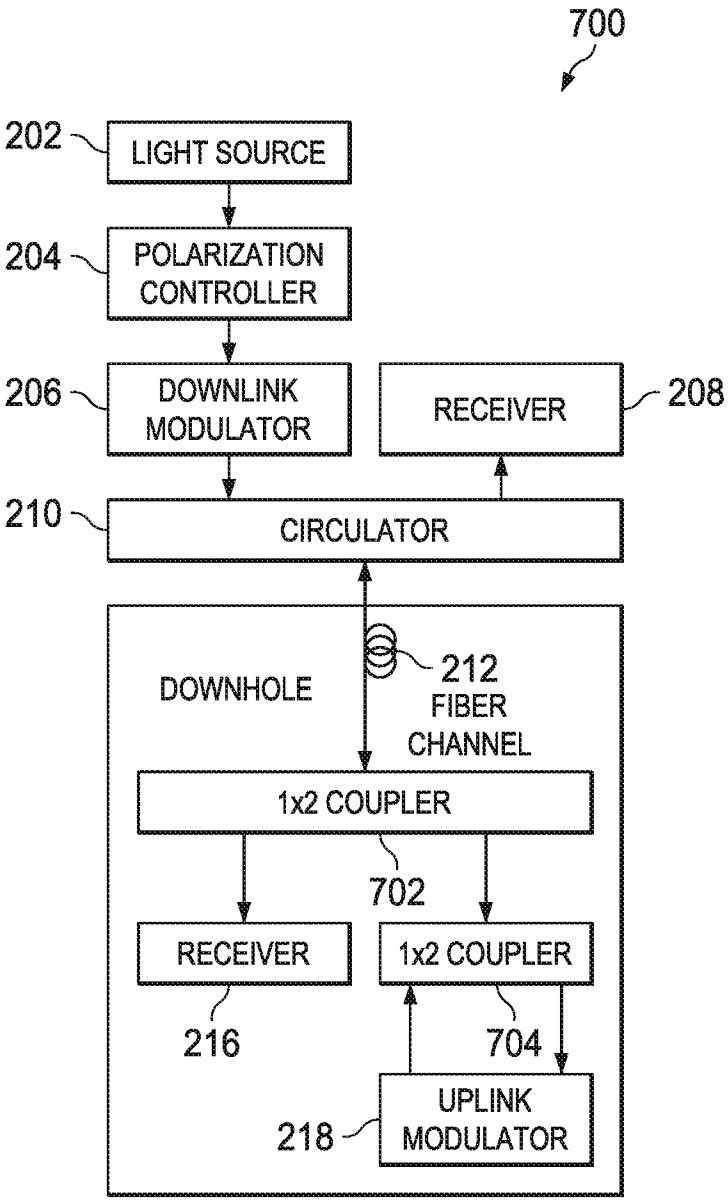

700
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
DOWNLINK MODULATOR
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x2 COUPLER
702
RECEIVER
1x2 COUPLER
216
704
218
UPLINK MODULATOR

FIG. 7

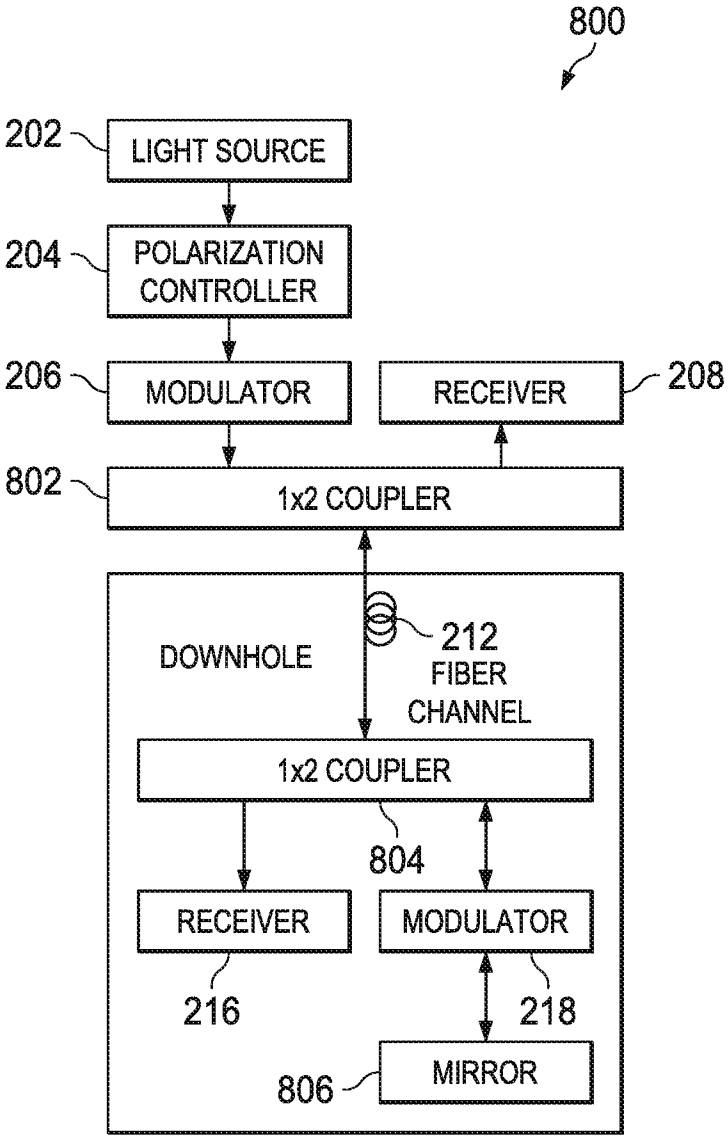

800
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
MODULATOR
RECEIVER
208
802
1x2 COUPLER
DOWNHOLE
212
FIBER CHANNEL
1x2 COUPLER
804
RECEIVER
MODULATOR
216
218
806
MIRROR

FIG. 8

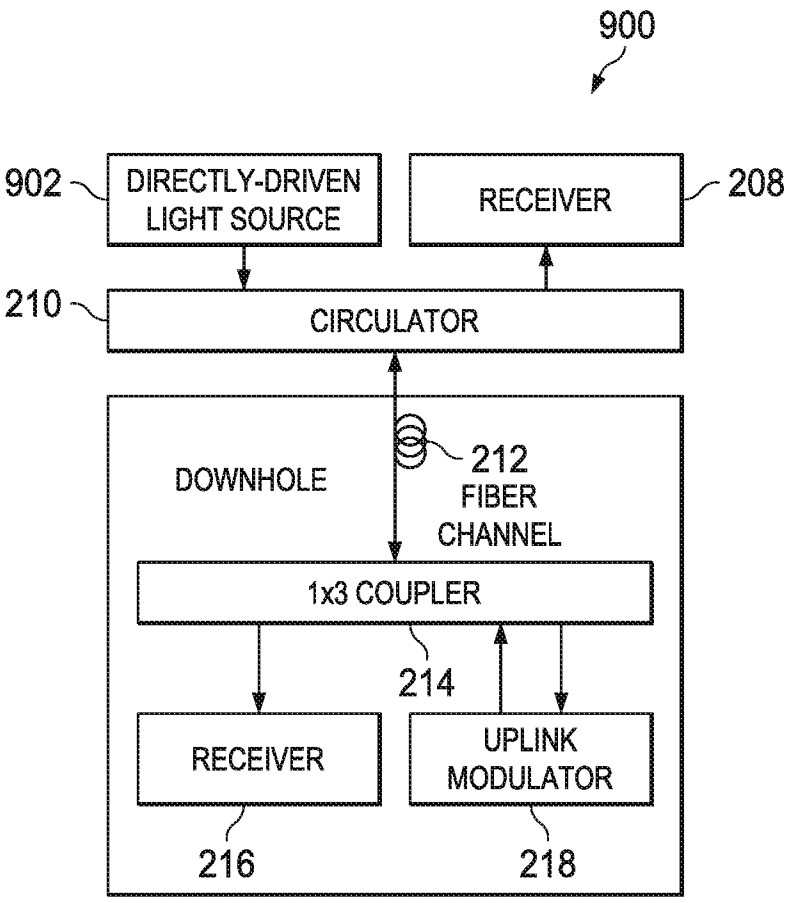

900
902
DIRECTLY-DRIVEN LIGHT SOURCE
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
UPLINK MODULATOR
216
218

FIG. 9

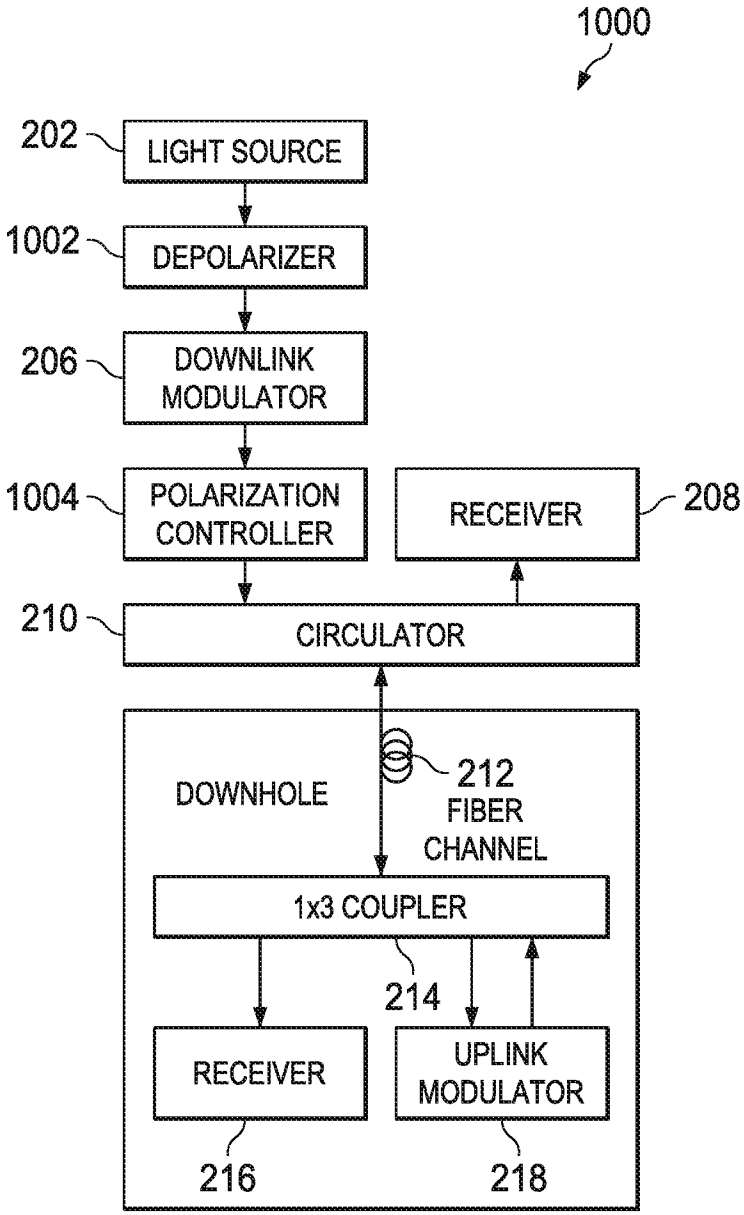

1000
202
LIGHT SOURCE
1002
DEPOLARIZER
206
DOWNLINK MODULATOR
1004
POLARIZATION CONTROLLER
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
UPLINK MODULATOR
216
218

FIG. 10A

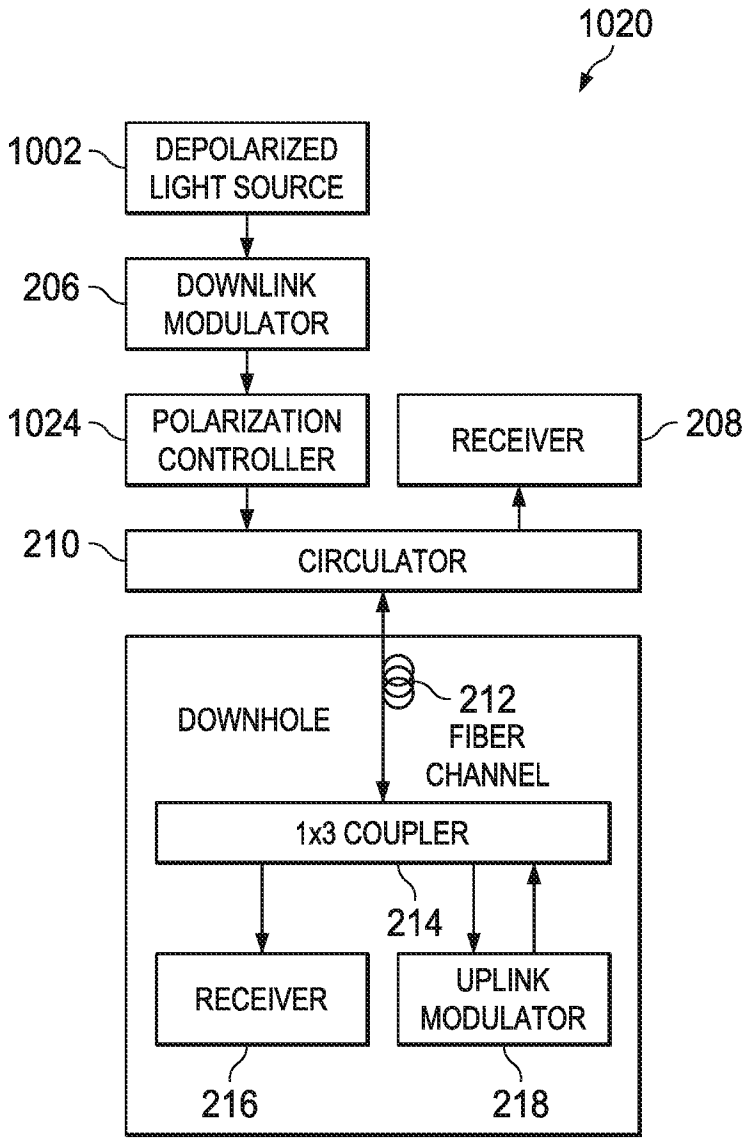

1020
1002
DEPOLARIZED LIGHT SOURCE
206
DOWNLINK MODULATOR
1024
POLARIZATION CONTROLLER
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
UPLINK MODULATOR
216
218

FIG. 10B

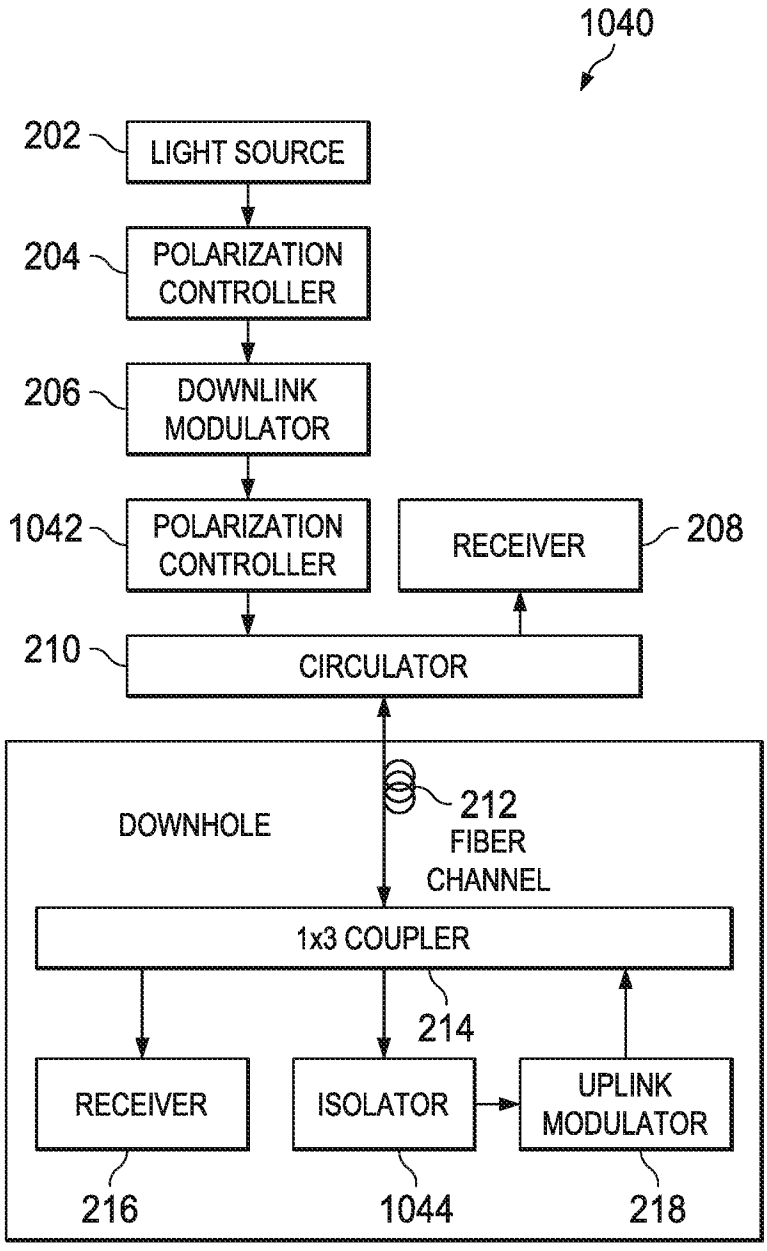

1040
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
206
DOWNLINK MODULATOR
1042
POLARIZATION CONTROLLER
RECEIVER
208
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
ISOLATOR
UPLINK MODULATOR
216
1044
218

FIG. 10C

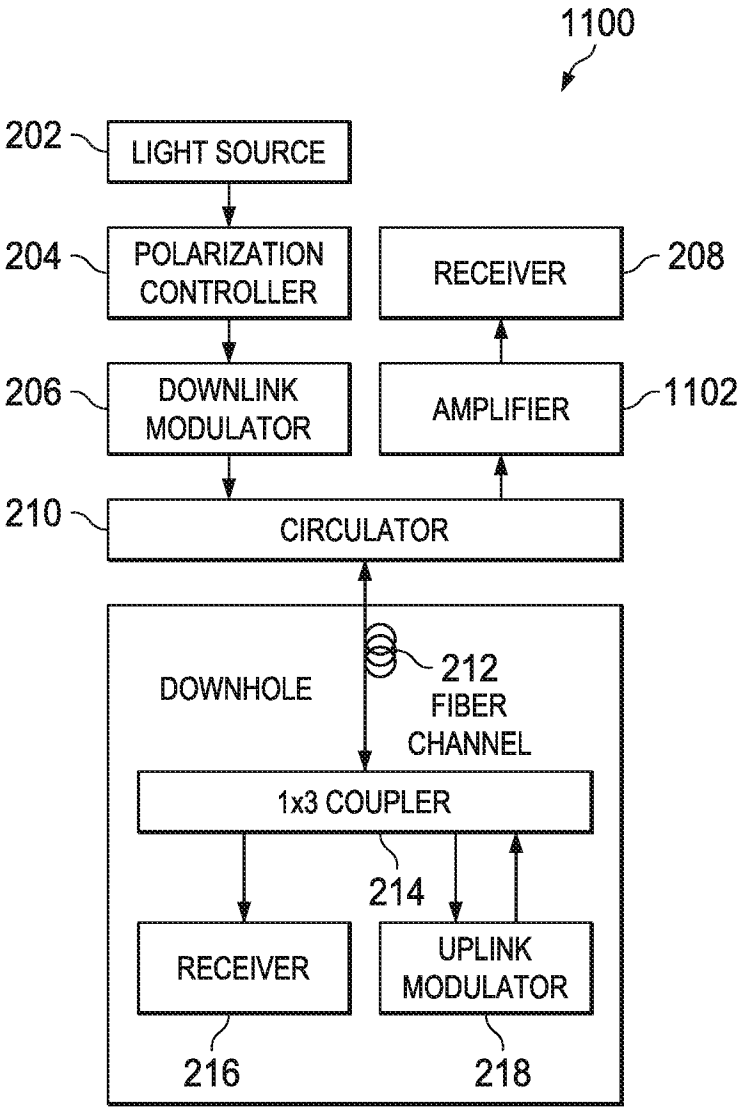

1100
202
LIGHT SOURCE
204
POLARIZATION CONTROLLER
208
RECEIVER
206
DOWNLINK MODULATOR
1102
AMPLIFIER
210
CIRCULATOR
DOWNHOLE
212
FIBER CHANNEL
1x3 COUPLER
214
RECEIVER
UPLINK MODULATOR
216
218

FIG. 11

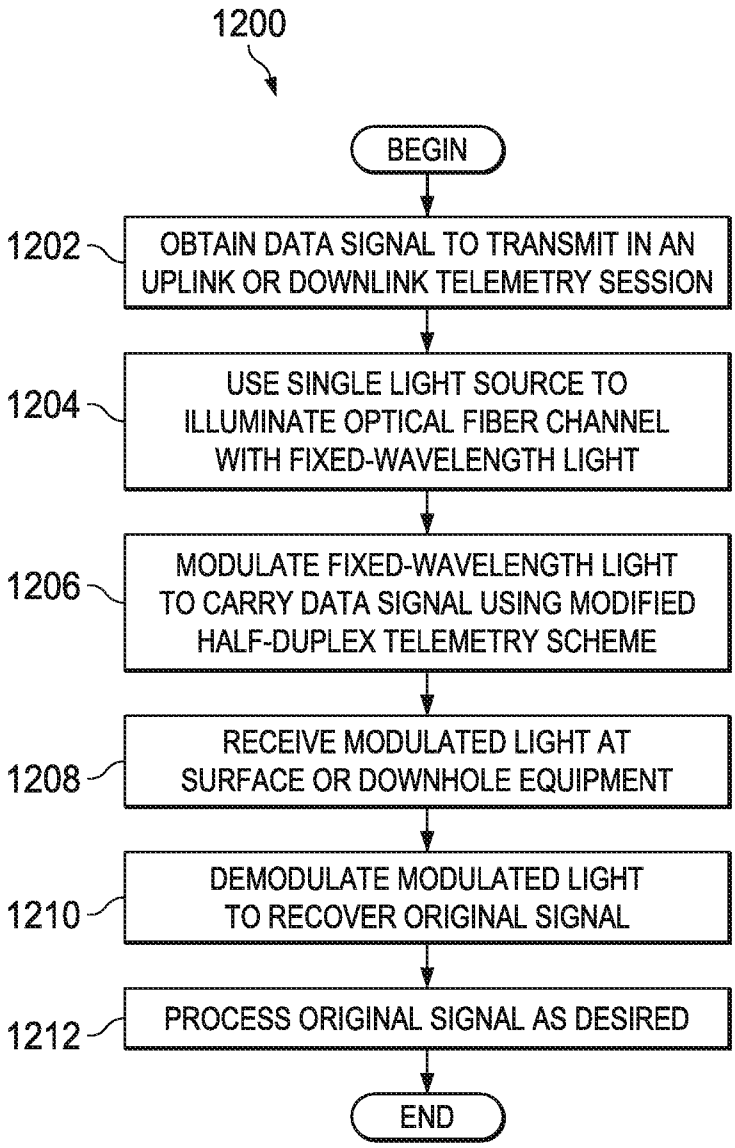

1200
BEGIN
1202
OBTAIN DATA SIGNAL TO TRANSMIT IN AN UPLINK OR DOWNLINK TELEMETRY SESSION
1204
USE SINGLE LIGHT SOURCE TO ILLUMINATE OPTICAL FIBER CHANNEL WITH FIXED-WAVELENGTH LIGHT
1206
MODULATE FIXED-WAVELENGTH LIGHT TO CARRY DATA SIGNAL USING MODIFIED HALF-DUPLEX TELEMETRY SCHEME
1208
RECEIVE MODULATED LIGHT AT SURFACE OR DOWNHOLE EQUIPMENT
1210
DEMODULATE MODULATED LIGHT TO RECOVER ORIGINAL SIGNAL
1212
PROCESS ORIGINAL SIGNAL AS DESIRED
END

FIG. 12

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/020038

A. CLASSIFICATION OF SUBJECT MATTER

E21B 47/12(2006.01)i, E21B 47/135(2012.01)i, E21B 17/00(2006.01)i

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)
E21B 47/12; G01V 3/00; G02B 6/26; E21B 49/00; G02B 6/34; E21B 7/15; G02B 6/00; E21B 47/135; E21B 17/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: fiber, optic, telemetry, fixed-wavelength, modulator, light, circulator, coupler, mirror, isolator, polarization

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007-0126594 A1 (ATKINSON et al.) 07 June 2007 See paragraphs [0001], [0007], [0014], [0029], [0043]-[0047], [0061]; and figures 1, 2A-2B.	1-13,17-20
Y	US 2002-0039465 A1 (SKINNER, NEAL G.) 04 April 2002 See paragraphs [0027], [0033]-[0043]; and figures 2-3, 5.	1-13,17-20
A	US 2012-0067118 A1 (HARTOG et al.) 22 March 2012 See paragraphs [0030]-[0038]; and figures 1-2.	1-13,17-20
A	US 2012-0273269 A1 (RINZLER et al.) 01 November 2012 See paragraphs [0056]-[0063]; and figure 5.	1-13,17-20
A	WO 2010-096086 A1 (FORO ENERGY INC. et al.) 26 August 2010 See paragraphs [0064]-[0089]; and figure 1.	1-13,17-20

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

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"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	Date of mailing of the international search report
15 November 2016 (15.11.2016)	**15 November 2016 (15.11.2016)**

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea
Facsimile No. +82-42-481-8578

Authorized officer
LEE, Jong Kyung
Telephone No. +82-42-481-3360

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/020038

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☒ Claims Nos.: 14-16
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/020038

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2007-0126594 A1	07/06/2007	CA 2568481 A1	06/06/2007
		GB 2433112 A	13/06/2007
		GB 2433112 B	09/07/2008
		GB 2433115 A	13/06/2007
		GB 2433115 B	16/04/2008
		MX PA06013948 A	16/10/2008
		NO 20065530 A	07/06/2007
		US 9000942 B2	07/04/2015
US 2002-0039465 A1	04/04/2002	CA 2424709 A1	11/04/2002
		CA 2424709 C	26/08/2008
		US 7072588 B2	04/07/2006
		WO 02-30011 A1	11/04/2002
US 2012-0067118 A1	22/03/2012	CA 2809660 A1	08/03/2012
		EP 2596387 A2	29/05/2013
		US 9170149 B2	27/10/2015
		WO 2012-030814 A2	08/03/2012
		WO 2012-030814 A3	31/05/2012
US 2012-0273269 A1	01/11/2012	US 9267330 B2	23/02/2016
WO 2010-096086 A1	26/08/2010	AU 2009-340454 A1	26/08/2010
		BR PI0918403 A2	24/11/2015
		CA 2734492 A1	26/08/2010
		CA 2823922 A1	26/08/2010
		CN 102187046 A	14/09/2011
		CN 102187046 B	29/04/2015
		EP 2315904 A1	04/05/2011
		EP 2399155 A1	28/12/2011
		JP 2012-500350 A	05/01/2012
		JP 2012-518210 A	09/08/2012
		JP 2015-017498 A	29/01/2015
		JP 5684151 B2	11/03/2015
		JP 5844868 B2	20/01/2016
		MX 2011001908 A	20/06/2011
		RU 2011-110388 A	27/09/2012
		RU 2522016 C2	10/07/2014
		US 2010-0044102 A1	25/02/2010
		US 2010-0044103 A1	25/02/2010
		US 2010-0044104 A1	25/02/2010
		US 2010-0044105 A1	25/02/2010
		US 2010-0044106 A1	25/02/2010
		US 2010-0215326 A1	26/08/2010
		US 2013-0175090 A1	11/07/2013
		US 2013-0192893 A1	01/08/2013
		US 2013-0192894 A1	01/08/2013
		US 2014-0060802 A1	06/03/2014
		US 2014-0060930 A1	06/03/2014

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/020038

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
		US 2015-0308194 A1	29/10/2015
		US 2015-0322738 A1	12/11/2015
		US 2016-0017661 A1	21/01/2016
		US 8424617 B2	23/04/2013
		US 8511401 B2	20/08/2013
		US 8636085 B2	28/01/2014
		US 8701794 B2	22/04/2014
		US 8757292 B2	24/06/2014
		US 8820434 B2	02/09/2014
		US 8826973 B2	09/09/2014
		US 8869914 B2	28/10/2014
		US 8936108 B2	20/01/2015
		US 8997894 B2	07/04/2015
		WO 2010-144160 A1	16/12/2010