



(19) **United States**

(12) **Patent Application Publication**  
**Chang et al.**

(10) **Pub. No.: US 2018/0069637 A1**

(43) **Pub. Date: Mar. 8, 2018**

(54) **OPTICAL TRANSMISSION SYSTEM AND RELATED REMOTE OPTICALLY PUMPED AMPLIFIER (ROPA) AND METHOD**

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(21) Appl. No.: **15/800,296**

(22) Filed: **Nov. 1, 2017**

**Related U.S. Application Data**

(63) Continuation of application No. 15/060,973, filed on Mar. 4, 2016, now Pat. No. 9,838,136.

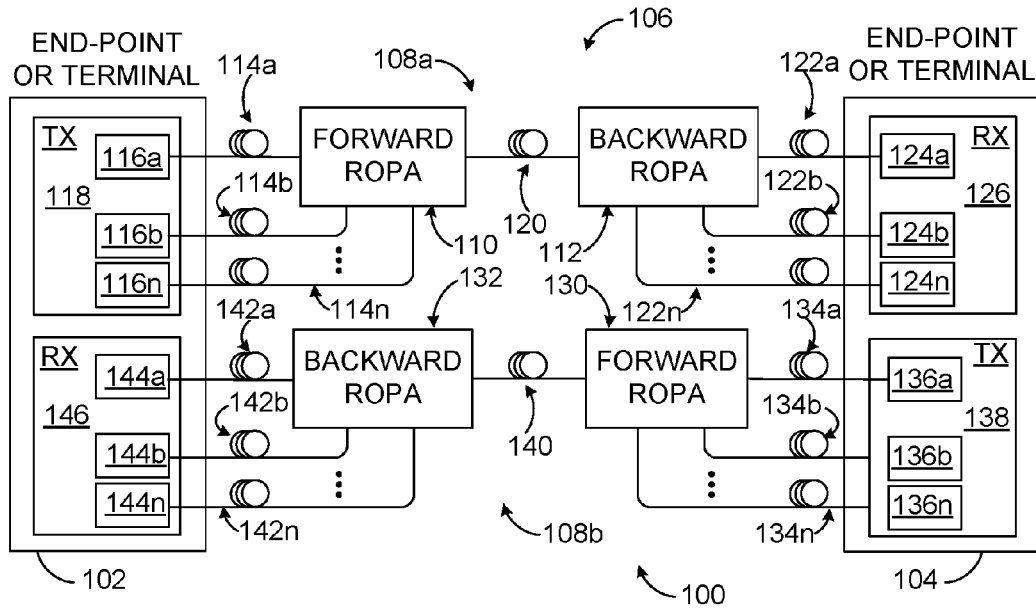
(60) Provisional application No. 62/129,610, filed on Mar. 6, 2015.

**Publication Classification**

(51) **Int. Cl.**  
*H04B 10/564* (2006.01)  
*H04B 10/291* (2006.01)  
*H01S 3/094* (2006.01)  
(52) **U.S. Cl.**  
CPC ..... *H04B 10/564* (2013.01); *H01S 3/094* (2013.01); *H04B 10/2916* (2013.01)

(57) **ABSTRACT**

An apparatus includes a remote optically pumped amplifier (ROPA). The ROPA includes a bypass filter configured to receive an optical signal and first pump power and to separate the optical signal and the first pump power. The ROPA also includes an amplifier configured to receive the optical signal from the bypass filter and to amplify the optical signal. The ROPA further includes an optical combiner/multiplexer configured to receive the first pump power from the bypass filter, receive at least second and third pump powers, combine at least two of the first, second and third pump powers, and provide different pump powers or combinations of pump powers to different locations within the ROPA to feed the amplifier.



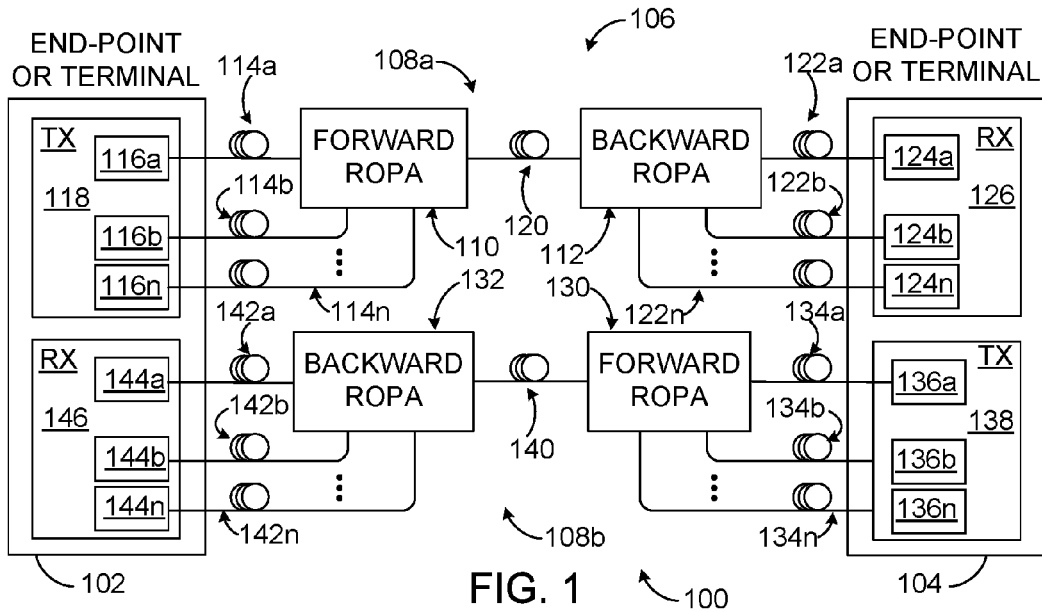


FIG. 1

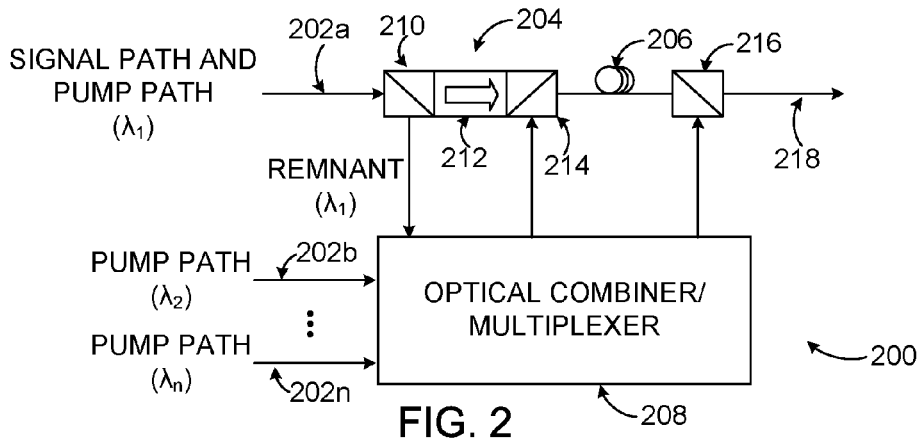


FIG. 2

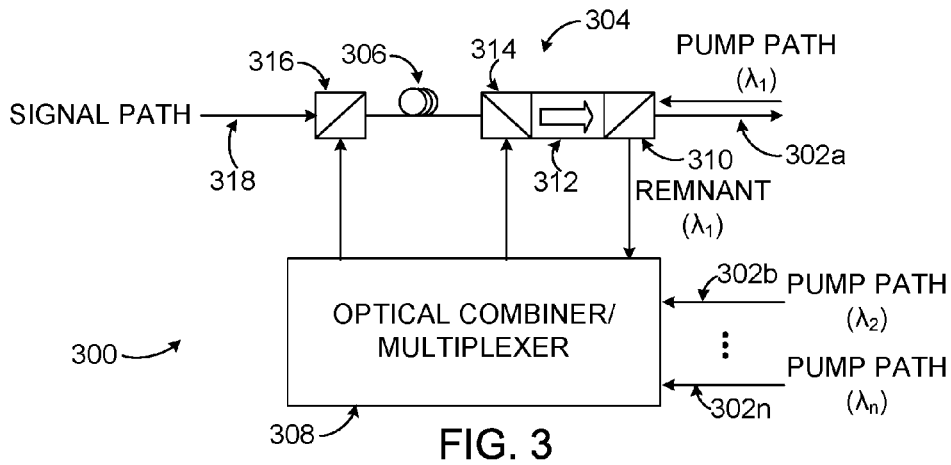


FIG. 3

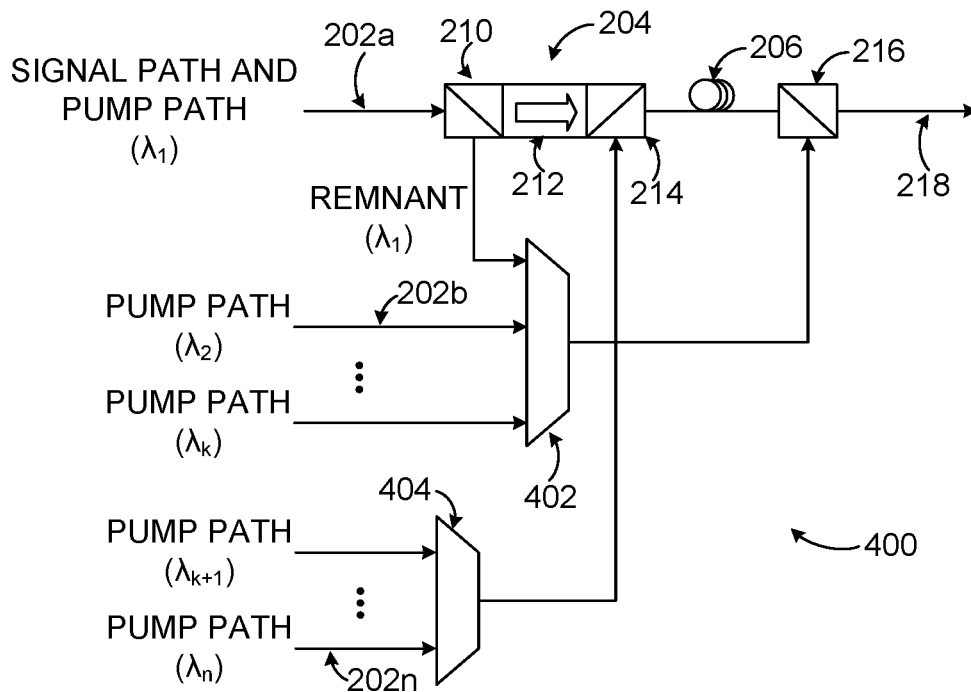


FIG. 4

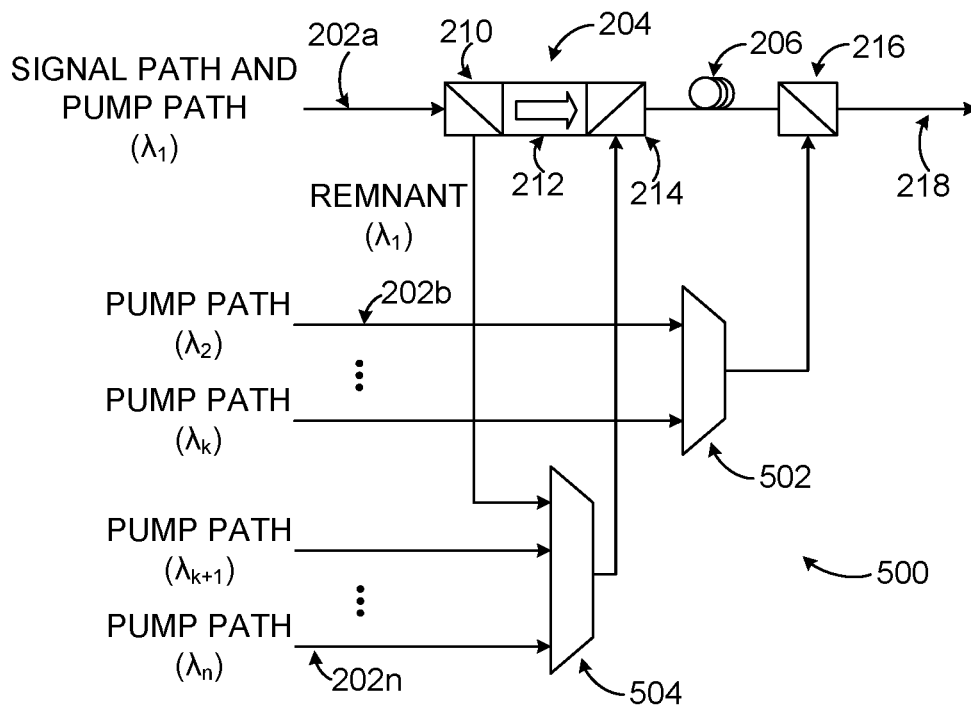


FIG. 5

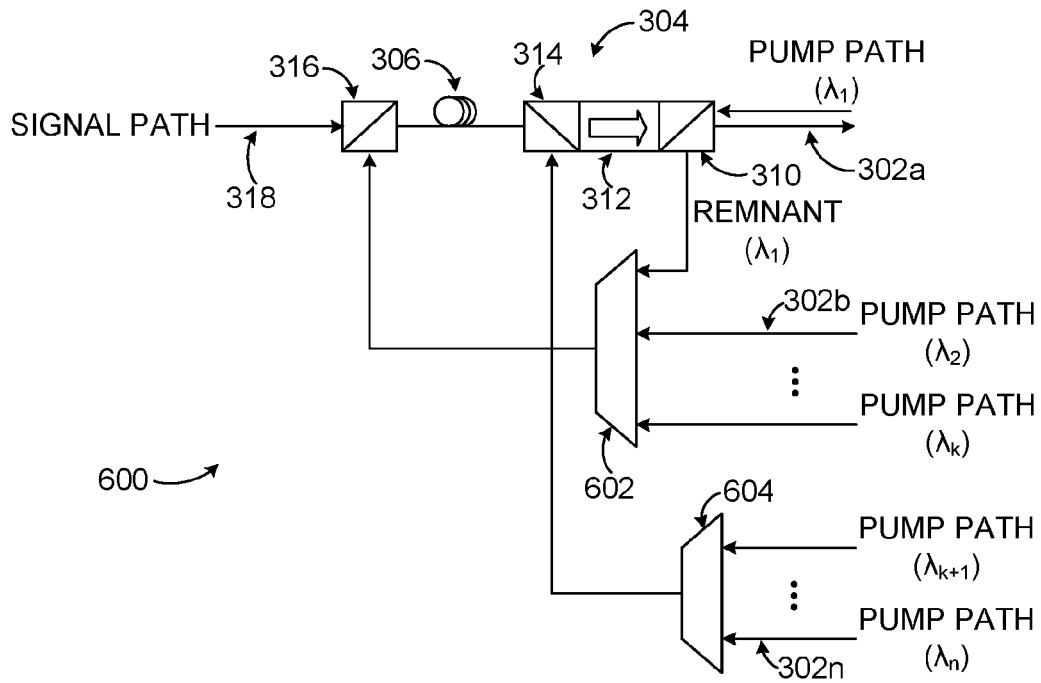


FIG. 6

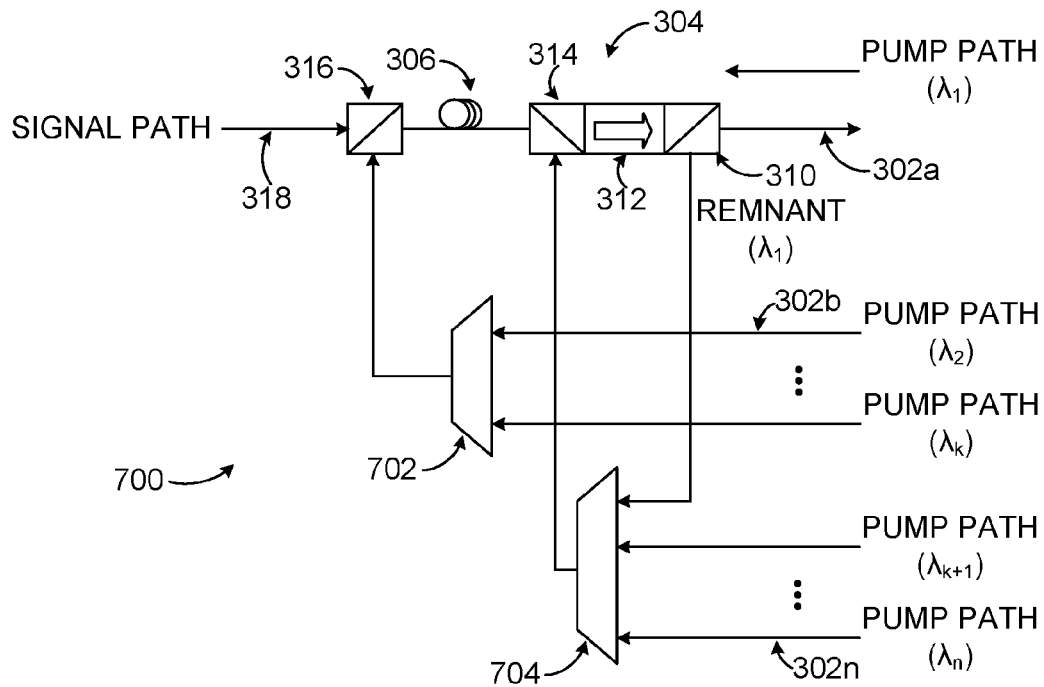


FIG. 7

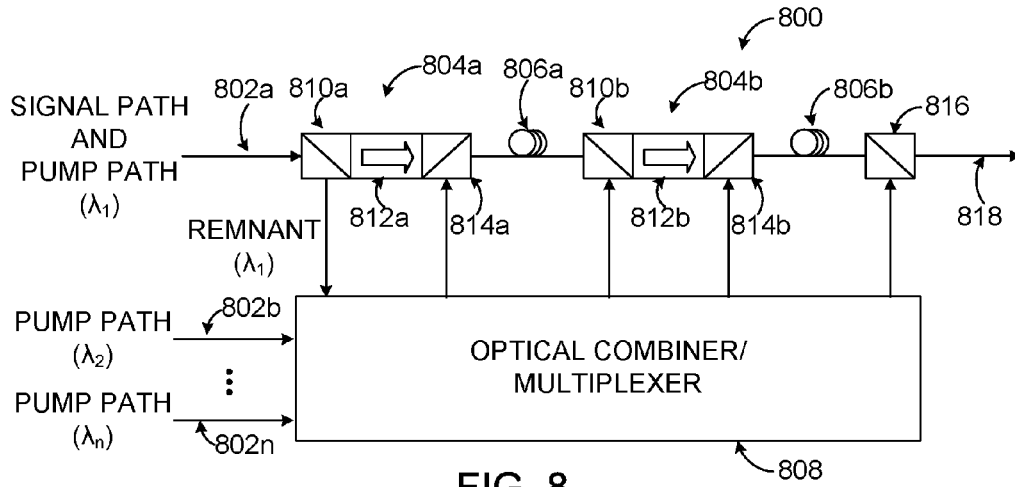


FIG. 8

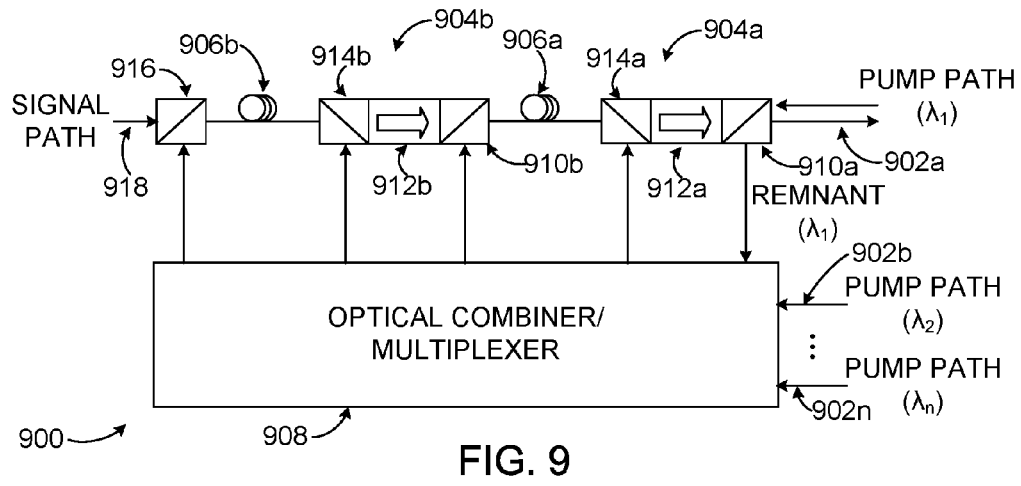


FIG. 9

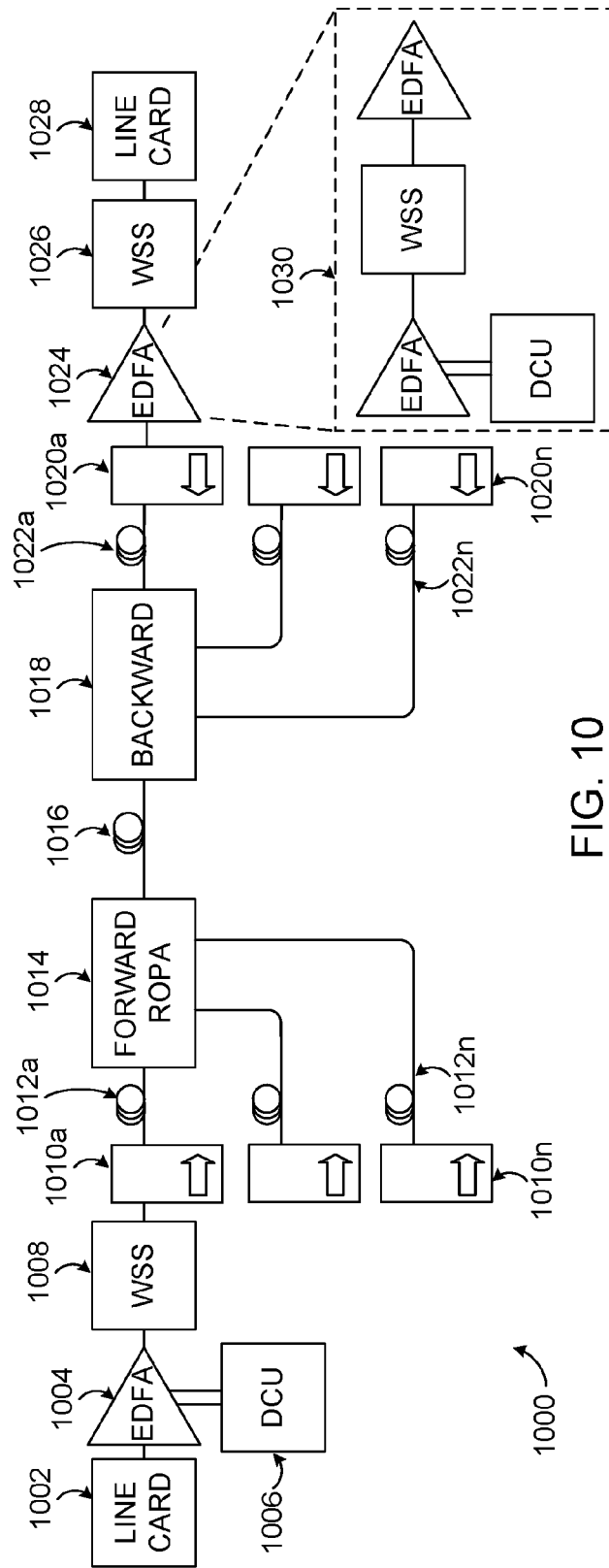


FIG. 10

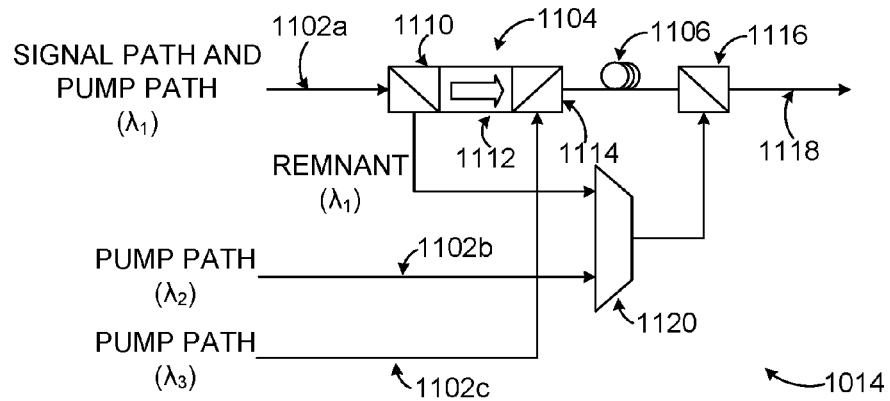


FIG. 11

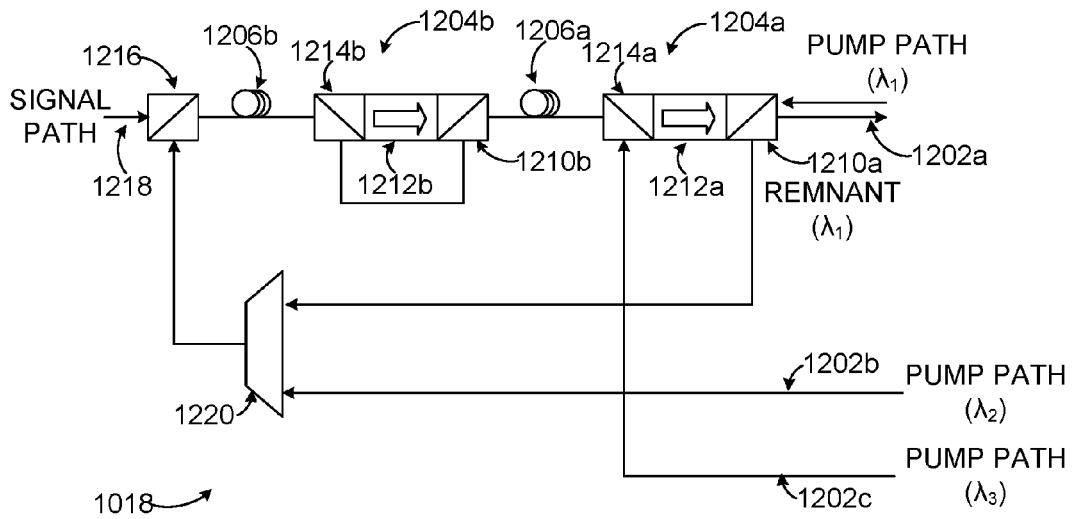


FIG. 12

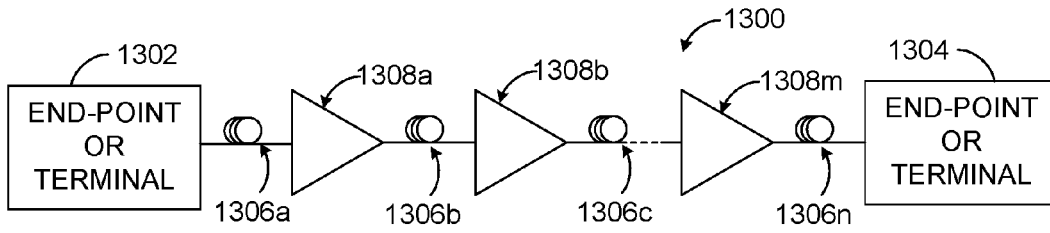


FIG. 13

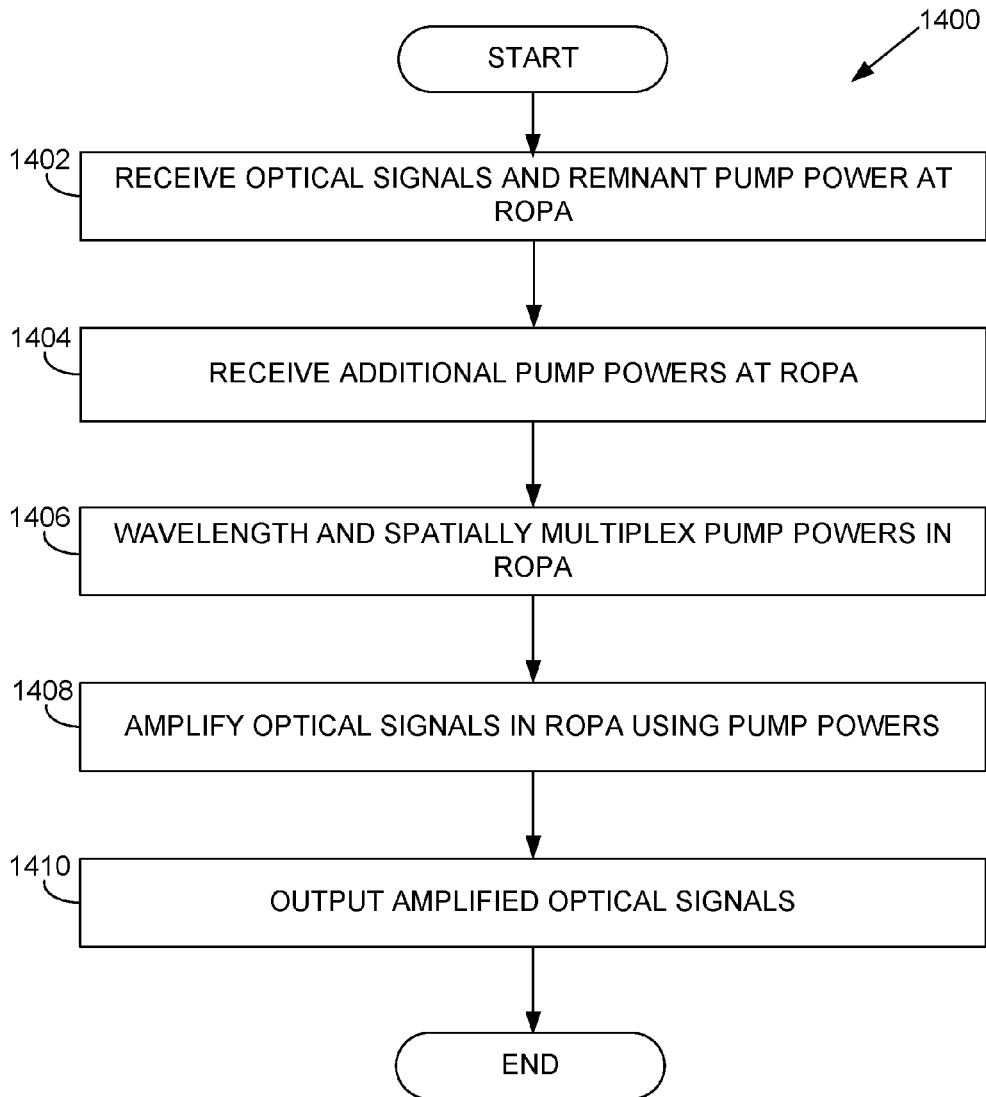


FIG. 14



## OPTICAL TRANSMISSION SYSTEM AND RELATED REMOTE OPTICALLY PUMPED AMPLIFIER (ROPA) AND METHOD

### CROSS-REFERENCE TO RELATED APPLICATION AND PRIORITY CLAIM

**[0001]** This application claims priority under 35 U.S.C. §119(e) to U.S. Provisional Patent Application No. 62/129,610 filed on Mar. 6, 2015. This provisional patent application is hereby incorporated by reference in its entirety.

### TECHNICAL FIELD

**[0002]** This disclosure relates generally to optical transmission systems. More specifically, this disclosure relates to an optical transmission system and a related remote optically pumped amplifier (ROPA) and method.

### BACKGROUND

**[0003]** Optical communication networks are often used to transport large amounts of data over long distances very quickly. At present, sophisticated optical communication networks are capable of transmitting tens of trillions of bits of information per second over a single optical fiber spanning many hundreds of kilometers. Optical communication networks generally exceed the bandwidth capabilities of copper networks. As a result, optical networks are often part of wireline telecommunication networks and are often used to provide optical backbones at the cores of the telecommunication networks.

### SUMMARY

**[0004]** This disclosure provides an optical transmission system and a related remote optically pumped amplifier (ROPA) and method.

**[0005]** In a first embodiment, an apparatus includes a ROPA. The ROPA includes a bypass filter configured to receive an optical signal and first pump power and to separate the optical signal and the first pump power. The ROPA also includes an amplifier configured to receive the optical signal from the bypass filter and to amplify the optical signal. The ROPA further includes an optical combiner/multiplexer configured to receive the first pump power from the bypass filter, receive at least second and third pump powers, combine at least two of the first, second and third pump powers, and provide different pump powers or combinations of pump powers to different locations within the ROPA to feed the amplifier.

**[0006]** In a second embodiment, a system includes an optical communication link having a ROPA. The ROPA includes a bypass filter configured to receive an optical signal and first pump power and to separate the optical signal and the first pump power. The ROPA also includes an amplifier configured to receive the optical signal from the bypass filter and to amplify the optical signal. The ROPA further includes an optical combiner/multiplexer configured to receive the first pump power from the bypass filter, receive at least second and third pump powers, combine at least two of the first, second and third pump powers, and provide different pump powers or combinations of pump powers to different locations within the ROPA to feed the amplifier.

**[0007]** In a third embodiment, a method includes receiving an optical signal and first pump power at a ROPA. The

method also includes separating the optical signal and the first pump power using a bypass filter of the ROPA. The method further includes amplifying the optical signal using an amplifier of the ROPA. The method also includes receiving the first pump power from the bypass filter and at least second and third pump powers at an optical combiner/multiplexer of the ROPA. In addition, the method includes combining at least two of the first, second and third pump powers and providing different pump powers or combinations of pump powers to different locations within the ROPA to feed the amplifier.

**[0008]** Other technical features may be readily apparent to one skilled in the art from the following figures, descriptions, and claims.

### BRIEF DESCRIPTION OF THE DRAWINGS

**[0009]** For a more complete understanding of this disclosure, reference is now made to the following description, taken in conjunction with the accompanying drawings, in which:

**[0010]** FIG. 1 illustrates an example optical transmission system according to this disclosure;

**[0011]** FIGS. 2 and 3 illustrate example architectures of remote optically pumped amplifiers (ROPAs) for use in optical transmission systems according to this disclosure;

**[0012]** FIGS. 4 through 7 illustrate specific examples of architectures of ROPAs for use in optical transmission systems according to this disclosure;

**[0013]** FIGS. 8 and 9 illustrate example multi-stage architectures of ROPAs for use in optical transmission systems according to this disclosure;

**[0014]** FIGS. 10 through 12 illustrate a specific example of an optical transmission system and related ROPAs according to this disclosure;

**[0015]** FIG. 13 illustrates an example multi-span optical transmission system according to this disclosure; and

**[0016]** FIG. 14 illustrates an example method for operating a ROPA in an optical transmission system according to this disclosure.

### DETAILED DESCRIPTION

**[0017]** FIGS. 1 through 14, discussed below, and the various embodiments used to describe the principles of the present invention in this patent document are by way of illustration only and should not be construed in any way to limit the scope of the invention. Those skilled in the art will understand that the principles of the invention may be implemented in any type of suitably arranged device or system.

**[0018]** This disclosure provides various architectures for remote optically pumped amplifiers (ROPAs) and optical transmission systems that utilize such ROPAs. In some embodiments, these ROPAs and optical transmission systems support the use of one or more unrepeated optical communication links. An “unrepeated” optical communication link refers to an optical link in which active optical repeaters are not used. In contrast, a “repeated” optical communication link refers to an optical link in which one or more active optical repeaters are used at one or more in-line optical amplification sites. One aspect differentiating repeated and unrepeated optical communication links is the fact that active optical repeaters need a source of electrical power, so a copper conductor is typically used in a cable for

a repeatered communication link in order to electrically power optical amplifiers within the active optical repeaters. Unrepeatered optical cables do not have the ability to supply electrical power to in-line equipment. Instead, conventional unrepeatered optical networks often use ROPAs to amplify optical signals as the optical signals traverse the optical links. Each ROPA is not electrically powered locally but is rather optically pumped from one end of a communication link, hence the terminology “remote optically pumped” amplifier.

[0019] Unrepeatered transmission systems have a number of potential applications including submarine and terrestrial optical communications, such as in optical fiber networks embedded into power cable systems of power utilities. In some instances, a ROPA is used on only the “receive side” of an unrepeatered optical link. In other instances, ROPAs are used on both the “transmit side” and the “receive side” of an unrepeatered optical link. The “transmit side” refers to the portion of an optical link closer to a transmitting end-point or terminal, and the “receive side” refers to the portion of an optical link closer to a receiving end-point or terminal. When optical fibers are used in pairs (one for transmission in one direction and another for transmission in the opposite direction), the ROPA on the transmit side of one optical fiber can be placed in the same housing as the ROPA on the receive side of the other optical fiber.

[0020] While often described below as being used in a single-span unrepeatered optical transmission system, the principles described in this patent document are not limited to such systems. The principles described in this patent document could find use in other systems, such as a multi-span optical transmission system in which multiple ROPAs are used in-line with multiple spans of optical fibers or in amplified optical transmission systems. In general, the principles described in this patent document can be used in any system where there is an optical span that is long and lossy or where remote optical amplification is otherwise needed or desired in an optical span. The use of one or more ROPAs in these types of optical links allows amplification of optical signals without the need for regeneration points.

[0021] FIG. 1 illustrates an example optical transmission system 100 according to this disclosure. As shown in FIG. 1, the system 100 includes a first end-point or terminal 102, a second end-point or terminal 104, and at least one optical communication link 106. The end-points or terminals 102 and 104 communicate with one another via the optical communication link 106 to exchange data. Each end-point or terminal 102 and 104 also typically communicates with external devices or systems. Each end-point or terminal 102 and 104 generally denotes any suitable device or system that communicates optically. Each end-point or terminal 102 and 104 could, for example, denote components on opposite sides of an optical communication link 106 that can span hundreds of kilometers over land or under water.

[0022] The optical communication link 106 here denotes a bi-directional optical link. The optical communication link 106 includes a first optical link 108a supporting optical transmissions from the first end-point or terminal 102 to the second end-point or terminal 104 and a second optical link 108b supporting optical transmissions from the second end-point or terminal 104 to the first end-point or terminal 102. The optical links 108a and 108b are often said to denote a “fiber pair.” Note that while two optical links in one fiber pair are shown in FIG. 1, any number of optical links or fiber

pairs could be used between the end-points or terminals 102 and 104. For ease of explanation, the structure of the optical link 108a is described in greater detail below, and the optical link 108b could have the same or similar configuration (although this need not be the case).

[0023] As shown here, the optical link 108a includes both a forward ROPA 110 and a backward ROPA 112. Each ROPA 110 and 112 denotes an optical amplifier that operates using pump power provided to the ROPA 110 and 112 through the optical link 108a. The ROPAs 110 and 112 need not be provided electrical power through a copper or other conductor in the optical link 108a. The ROPA 110 is referred to as a “forward” ROPA because the pump power used by the ROPA 110 flows from the end-point or terminal 102 to the ROPA 110 in the same direction as optical signals sent from the end-point or terminal 102 to the end-point or terminal 104. In contrast, the ROPA 112 is referred to as a “backward” ROPA because the pump power used by the ROPA 112 flows from the end-point or terminal 104 to the ROPA 112 in an opposite direction as the optical signals sent from the end-point or terminal 102 to the end-point or terminal 104.

[0024] The ROPA 110 is coupled to the end-point or terminal 102 by three or more optical fibers 114a-114n. Optical signals containing data sent from the end-point or terminal 102 to the end-point or terminal 104 travel over the optical fiber 114a to the ROPA 110. Pump power for the ROPA 110 is sent from various pump sources 116a-116n in an optical transmitter 118 of the end-point or terminal 102 through the optical fibers 114a-114n. The ROPA 110 operates to amplify the optical signals received over the optical fiber 114a using the pump power received over the optical fibers 114a-114n. As described in more detail below, the ROPA 110 implements spatial and wavelength multiplexing to more effectively use the pump power from the pump sources 116a-116n in order to amplify the optical signals traveling through the optical link 108a.

[0025] The ROPA 110 includes any suitable remotely-pumped structure for optically amplifying signals. Each of the optical fibers 114a-114n includes any suitable optical fiber for transporting optical signals or pump power. In some instances, each of the optical fibers 114a-114n could have a length of over 100 or 120 kilometers. Each of the pump sources 116a-116n includes any suitable structure for providing pump power to a remote optical amplifier. Each of the pump sources 116a-116n could, for instance, denote one or more lasers. The optical transmitter 118 includes any suitable structure for generating optical signals for transmission over an optical link.

[0026] An optical fiber 120 couples the forward ROPA 110 and the backward ROPA 112. The optical fiber 120 includes any suitable optical fiber for transporting optical signals. In some instances, the optical fiber 120 could have a length of over 500 or 600 kilometers.

[0027] The backward ROPA 112 operates in a similar manner as the forward ROPA 110, but the direction that the pump power travels is reversed. The ROPA 112 is coupled to the end-point or terminal 104 by three or more optical fibers 122a-122n. Optical signals containing data sent from the end-point or terminal 102 to the end-point or terminal 104 travel over the optical fiber 122a to the end-point or terminal 104. Pump power for the ROPA 112 is sent from various pump sources 124a-124n in an optical receiver 126 of the end-point or terminal 104 through the optical fibers

**122a-122n.** The ROPA **112** operates to amplify the optical signals received over the optical fiber **120** using the pump power received over the optical fibers **122a-122n**. As described in more detail below, the ROPA **112** implements spatial and wavelength multiplexing to more effectively use the pump power from the pump sources **124a-124n** in order to amplify the optical signals traveling through the optical link **108a**.

**[0028]** The ROPA **112** includes any suitable remotely-pumped structure for optically amplifying signals. Each of the optical fibers **122a-122n** includes any suitable optical fiber for transporting optical signals or pump power. In some instances, each of the optical fibers **122a-122n** could have a length of over 150 kilometers. Each of the pump sources **124a-124n** includes any suitable structure for providing pump power to a remote optical amplifier. Each of the pump sources **124a-124n** could, for instance, denote one or more lasers. The optical receiver **126** includes any suitable structure for processing optical signals received over an optical link.

**[0029]** Communications from the end-point or terminal **104** to the end-point or terminal **102** over the optical link **108b** could occur in the same or similar manner. The optical link **108b** includes a forward ROPA **130** and a backward ROPA **132**. The forward ROPA **130** is coupled to the end-point or terminal **104** by three or more optical fibers **134a-134n**, and pump sources **136a-136n** of an optical transmitter **138** provide pump power to the ROPA **130**. The forward ROPA **130** is coupled to the backward ROPA **132** by an optical fiber **140**. The backward ROPA **132** is coupled to the end-point or terminal **102** by three or more optical fibers **142a-142n**, and pump sources **144a-144n** of an optical receiver **146** provide pump power to the ROPA **132**.

**[0030]** Each ROPA **130** and **132** includes any suitable remotely-pumped structure for optically amplifying signals. In some instances, the ROPAs **110** and **132** could be placed in a common housing, and the ROPAs **112** and **130** could be placed in a common housing. Each of the optical fibers **134a-134n**, **142a-142n** includes any suitable optical fiber for transporting optical signals or pump power. In some instances, each of the optical fibers **134a-134n** could have a length of over 100 or 120 kilometers, and each of the optical fibers **142a-142n** could have a length of over 150 kilometers. Each of the pump sources **136a-136n**, **144a-144n** includes any suitable structure for providing pump power to a remote optical amplifier, such as one or more lasers. The optical transmitter **138** includes any suitable structure for generating optical signals for transmission over an optical link. The optical receiver **146** includes any suitable structure for processing optical signals received over an optical link.

**[0031]** In some embodiments, Raman amplification can occur in the optical links **114a**, **122a**, **134a**, **142a** using pump power from the pump sources **116a**, **124a**, **136a**, **144a**. Any residual pump power sent over the optical links **114a**, **122a**, **134a**, **142a** and received at the ROPAs **110**, **112**, **130**, **132** could be referred to as a “remnant” of the pump power. As described in more detail below, the spatial and wavelength multiplexing provided by the ROPAs **110**, **112**, **130**, **132** can involve (i) any remnant pump powers received over the optical links **114a**, **122a**, **134a**, **142a** and (ii) at least two additional pump powers received over the optical links **114b-114n**, **122b-122n**, **134b-134n**, **142b-142n**. In some embodiments, the Raman amplification provided in the communication link **106** could denote first-order Raman

amplification or fractional-order Raman amplification but not multi-order Raman amplification. This means that optical signals can be directly pumped with a shift of one Raman order or with a fractional shift of one Raman order. A system capable of providing fractional-order Raman amplification is described in U.S. Pat. No. 7,567,593, which is hereby incorporated by reference in its entirety.

**[0032]** Although FIG. 1 illustrates one example of an optical transmission system **100**, various changes may be made to FIG. 1. For example, FIG. 1 is meant to illustrate one example environment in which certain ROPA architectures could be used. There are a number of single-span and multi-span configurations that could benefit from the use of these ROPA architectures, and FIG. 1 does not limit this disclosure to use of a ROPA architecture in any specific system. One example of a multi-span configuration containing ROPAs is disclosed in U.S. Patent Publication No. 2015/0270676, which is hereby incorporated by reference in its entirety. Also, while shown as including both forward and backward ROPAs **110**, **112**, **130**, **132** on each optical link **108a-108b**, an optical link could include only one of these ROPAs. Further, there is no requirement that the same design be used for the optical links **108a-108b**. In addition, any specific ROPA architectures discussed below could be replicated and used in any number of optical links and fiber pairs between components of the optical transmission system **100** or other optical transmission system.

**[0033]** FIGS. 2 and 3 illustrate example architectures of ROPAs for use in optical transmission systems according to this disclosure. For ease of explanation, the ROPA architectures in FIGS. 2 and 3 may be described as operating in the optical transmission system **100** of FIG. 1. However, these ROPA architectures could be used in any other suitable system.

**[0034]** In FIG. 2, a ROPA architecture **200** for a forward ROPA is illustrated. The ROPA architecture **200** here includes at least three optical paths **202a-202n**, which denote the optical paths through which optical signals and pump power flow to the forward ROPA. The optical paths **202a-202n** could, for instance, denote or be coupled to the optical fibers **114a-114n** or **134a-134n** in FIG. 1.

**[0035]** The optical path **202a** transports optical signals being communicated between the end-points or terminals **102** and **104** to the forward ROPA. The optical signals could denote any suitable optical signals. In some embodiments, the optical signals denote Wavelength Division Multiplexing (WDM) or Dense Wavelength Division Multiplexing (DWDM) signals. These types of optical signals generally denote signals formed by wavelength multiplexing of optical carriers at different frequencies. In the most basic case, there may be only one optical carrier for a signal, but there are generally multiple optical carriers in WDM or DWDM signals.

**[0036]** The optical paths **202a-202n** also transport pump power to the forward ROPA for use in amplifying the optical signals. Each pump power traveling over the optical paths **202a-202n** has an associated wavelength or wavelength range denoted  $\lambda_{\{1-n\}}$ . Although the different pump powers in FIG. 2 are associated with wavelengths or wavelength ranges  $\lambda_1$  through  $\lambda_n$ , this does not necessarily require that each optical path **202a-202n** transport pump power at a different wavelength or wavelength range. It is possible for some of the pump powers transported over different optical paths **202a-202n** to partially or completely overlap in wave-

length, as long as there are pump powers having at least three distinct wavelengths transported over the optical paths **202a-202n**.

[0037] As noted above, the pump power sent over the optical fiber **114a**, **134a** could be used for Raman amplification. As a result, only part of the pump power sent over the optical fiber **114a**, **134a** (the “remnant” pump power) may be received by the forward ROPA over the optical path **202a**.

[0038] The ROPA architecture **200** includes a bypass hybrid filter **204**, a fiber amplifier **206**, and an optical combiner/multiplexer unit **208**. The hybrid filter **204** generally operates to separate the optical signals received over the optical path **202a** from any remnant pump power received over the optical path **202a**, provide the optical signals to the fiber amplifier **206**, and provide the remnant pump power to the optical combiner/multiplexer unit **208**. The fiber amplifier **206** generally operates to amplify optical signals using pump power received at one or more locations of the ROPA architecture **200**. The optical combiner/multiplexer unit **208** supports both spatial and wavelength multiplexing of the pump powers and the ability to provide the pump powers to different locations within the ROPA architecture **200**.

[0039] In this example, the hybrid filter **204** is formed using an optical demultiplexer **210**, an optical isolator **212**, and an optical multiplexer **214**. There is an additional optical multiplexer **216** following the fiber amplifier **206**, which generates output signals on an optical path **218**. The optical path **218** could, for example, denote or be coupled to the optical fiber **120** or **140** in FIG. 1.

[0040] The optical demultiplexer **210** operates to separate the optical signals from the remnant pump power received over the optical path **202a**. The optical demultiplexer **210** provides the optical signals to the optical multiplexer **214** via the optical isolator **212**, and the optical demultiplexer **210** provides the remnant pump power to the optical combiner/multiplexer unit **208**. The optical isolator **212** operates to isolate the remnant pump power from passing through to the optical multiplexer **214**. The optical multiplexers **214** and **216** operate to combine the optical signals with pump powers provided by the optical combiner/multiplexer unit **208** onto common optical fibers. The optical multiplexer **214** feeds the fiber amplifier **206** in the forward direction, and the optical multiplexer **216** feeds the fiber amplifier **206** in the backward direction. The result here is that different pump powers can travel at least partially through the ROPA architecture **200** along paths that are parallel with the optical signals being amplified, and the pump powers can be fed in different directions to the fiber amplifier **206**.

[0041] The optical demultiplexer **210** includes any suitable structure for separating optical signals and pump powers. The optical isolator **212** includes any suitable structure for isolating optical signals and pump powers. Each of the optical multiplexers **214** and **216** includes any suitable structure for combining optical signals and pump powers. In some embodiments, a ROPA with a bypass component can be implemented as disclosed in U.S. patent application Ser. No. 13/214,010, which is hereby incorporated by reference in its entirety.

[0042] The fiber amplifier **206** denotes any suitable optical fiber structure configured to amplify optical signals. In some embodiments, the fiber amplifier **206** denotes an Erbium-doped fiber amplifier, although other suitable fiber amplifiers or other types of amplifiers could also be used.

[0043] The optical combiner/multiplexer unit **208** operates to redirect and selectively combine the pump powers received from the optical paths **202a-202n** and to provide the pump powers to the optical multiplexers **214** and **216**. As noted above, the optical combiner/multiplexer unit **208** provides both wavelength and spatial multiplexing of the pump powers. Wavelength multiplexing is accomplished by combining pump powers at different wavelengths or wavelength ranges. Spatial multiplexing is accomplished by providing pump powers to different locations within the ROPA architecture **200**, such as by providing different pump powers to different optical multiplexers **214** and **216**. Various implementations of the optical combiner/multiplexer unit **208** are described below.

[0044] The optical combiner/multiplexer unit **208** can be coupled to each of the components **210**, **214**, **216** via an optical fiber. Each of the locations where the optical combiner/multiplexer unit **208** can provide pump powers (to the optical multiplexers **214** and **216** in this example) may be referred to as a port. The optical combiner/multiplexer unit **208** therefore provides spatial and wavelength multiplexing between its three input optical fibers and the two ports. Note that while the optical combiner/multiplexer unit **208** is shown here as providing pump power to two locations, there could be additional locations where pump power can be provided. For example, pump power could be injected into different segments of the fiber amplifier **206**.

[0045] In FIG. 3, a ROPA architecture **300** for a backward ROPA is illustrated. The ROPA architecture **300** here includes at least three optical paths **302a-302n**, which denote the optical paths through which pump power flows to the backward ROPA and optical signals flow from the backward ROPA. The optical paths **302a-302n** could, for instance, denote or be coupled to the optical fibers **122a-122n** or **142a-142n** in FIG. 1.

[0046] The optical path **302a** transports optical signals being communicated between the end-points or terminals **102** and **104** from the backward ROPA to the end-point or terminal **104**. The optical signals could denote any suitable optical signals, such as WDM or DWDM signals. The optical paths **302a-302n** also transport pump power to the backward ROPA for use in amplifying the optical signals. The pump power traveling over the optical path **302a** travels in the opposite direction as the optical signals. Each pump power traveling over the optical paths **302a-302n** has an associated wavelength or wavelength range  $\lambda_{\{1-n\}}$ . Again, although the different pump powers in FIG. 3 are associated with wavelengths or wavelength ranges  $\lambda_1$  through  $\lambda_n$ , this does not necessarily require that each optical path **302a-302n** transport pump power at a different wavelength or wavelength range. It is possible for some of the pump powers transported over different optical paths **302a-302n** to partially or completely overlap in wavelength, as long as there are pump powers having at least three distinct wavelengths transported over the optical paths **302a-302n**.

[0047] As noted above, the pump power sent over the optical fiber **122a**, **142a** could be used for Raman amplification. As a result, only a remnant of the pump power sent over the optical fiber **122a**, **142a** may be received by the backward ROPA over the optical path **302a**.

[0048] The ROPA architecture **300** includes a bypass hybrid filter **304**, a fiber amplifier **306**, and an optical combiner/multiplexer unit **308**. The hybrid filter **304** generally operates to separate optical signals received over an

optical path **318** from any remnant pump power received over the optical path **302a**, provide the optical signals to the optical path **302a**, and provide the remnant pump power to the optical combiner/multiplexer unit **308**. The fiber amplifier **306** generally operates to amplify optical signals using pump power received at one or more locations of the ROPA architecture **300**. The optical combiner/multiplexer unit **308** supports both spatial and wavelength multiplexing of the pump powers and the ability to provide the pump powers to different locations within the ROPA architecture **300**.

[0049] In this example, the hybrid filter **304** is formed using an optical demultiplexer **310**, an optical isolator **312**, and an optical multiplexer **314**. There is an additional optical multiplexer **316** preceding the fiber amplifier **306**, which receives optical signals on the optical path **318**. The optical path **318** could, for example, denote or be coupled to the optical fiber **120** or **140** in FIG. 1.

[0050] The optical demultiplexer **310** operates to separate the optical signals from the remnant pump power received over the optical path **302a**. The optical demultiplexer **310** provides the optical signals to the optical path **302a**, and the optical demultiplexer **310** provides the remnant pump power to the optical combiner/multiplexer unit **308**. The optical isolator **312** operates to isolate the remnant pump power from passing through to the optical multiplexer **314**. The optical multiplexers **314** and **316** operate to combine the optical signals with pump powers provided by the optical combiner/multiplexer unit **308** onto common optical fibers. The optical multiplexer **316** feeds the fiber amplifier **306** in the forward direction, and the optical multiplexer **314** feeds the fiber amplifier **306** in the backward direction. The result here is that different pump powers can travel at least partially through the ROPA architecture **300** along paths that are parallel with the optical signals being amplified, and the pump powers can be fed in different directions to the fiber amplifier **306**.

[0051] The optical demultiplexer **310** includes any suitable structure for separating optical signals and pump powers. The optical isolator **312** includes any suitable structure for isolating optical signals and pump powers. Each of the optical multiplexers **314** and **316** includes any suitable structure for combining optical signals and pump powers. Again, in some embodiments, a ROPA with a bypass component can be implemented as disclosed in U.S. patent application Ser. No. 13/314,010.

[0052] The fiber amplifier **306** denotes any suitable optical fiber structure configured to amplify optical signals. In some embodiments, the fiber amplifier **306** denotes an Erbium-doped fiber amplifier, although other suitable fiber amplifiers or other types of amplifiers could also be used.

[0053] The optical combiner/multiplexer unit **308** operates to redirect and selectively combine the pump powers received from the optical paths **302a-302n** and to provide the pump powers to the optical multiplexers **314** and **316**. Again, the optical combiner/multiplexer unit **308** provides both wavelength and spatial multiplexing of the pump powers. Various implementations of the optical combiner/multiplexer unit **308** are described below.

[0054] The optical combiner/multiplexer unit **308** can be coupled to each of the components **310**, **314**, **316** via an optical fiber. Each of the locations where the optical combiner/multiplexer unit **308** can provide pump powers (to the optical multiplexers **314** and **316** in this example) may be referred to as a port. The optical combiner/multiplexer unit

**308** therefore provides spatial and wavelength multiplexing between its three input optical fibers and the two ports. Note that while the optical combiner/multiplexer unit **308** is shown here as providing pump power to two locations, there could be additional locations where pump power can be provided. For example, pump power could be injected into different segments of the fiber amplifier **306**.

[0055] In FIGS. 2 and 3, the forward and backward ROPA architectures **200** and **300** allow different pump powers to be both spatially and wavelength multiplexed within the ROPAs. The bypass components allow the optical signals being amplified to pass, while the pump powers can be provided to appropriate locations within the ROPAs to support more efficient and effective amplification of the optical signals. This can be accomplished without requiring the optical fibers that carry only pump powers to extend across the complete span between the end-points or terminals **102** and **104**. Rather, each optical fiber that carries only pump power may extend only to the closest ROPA.

[0056] Although FIGS. 2 and 3 illustrate examples of architectures **200**, **300** of ROPAs for use in optical transmission systems, various changes may be made to FIGS. 2 and 3. For example, the numbers of optical paths carrying pump powers can vary as needed or desired. Also, the numbers of inputs and outputs of the various optical combiner/multiplexer units can vary as needed or desired.

[0057] FIGS. 4 through 7 illustrate specific examples of architectures of ROPAs for use in optical transmission systems according to this disclosure. In particular, FIGS. 4 through 7 illustrate ROPAs with specific implementations of the optical combiner/multiplexer units **208** and **308** described above. For ease of explanation, the ROPA architectures in FIGS. 4 through 7 may be described as operating in the optical transmission system **100** of FIG. 1. However, these ROPA architectures could be used in any other suitable system.

[0058] As shown in FIG. 4, a forward ROPA architecture **400** includes various components **202a-202n**, **204**, **206**, **210**, **212**, **214**, **216**, **218** described above with respect to FIG. 2. The forward ROPA architecture **400** also implements the optical combiner/multiplexer unit **208** using two pump combiners **402** and **404**. Each pump combiner **402** and **404** denotes any suitable pump combiner, multiplexer, or other structure(s) configured to combine pump powers. While each pump combiner **402** and **404** is shown as a single component in FIG. 4, each pump combiner **402** and **404** could be implemented using multiple devices to perform the desired combining function.

[0059] In this example, the pump combiner **402** receives the remnant of the pump power from the optical path **202a** and pump powers from a subset of the remaining optical paths **202b-202n**. The pump combiner **404** receives pump powers from another subset of the remaining optical paths **202b-202n**. The pump combiner **404** feeds pump power(s) to the optical multiplexer **214**, while the pump combiner **402** feeds pump power(s) to the optical multiplexer **216**.

[0060] As shown in FIG. 5, a forward ROPA architecture **500** includes various components **202a-202n**, **204**, **206**, **210**, **212**, **214**, **216**, **218** described above with respect to FIG. 2. The forward ROPA architecture **500** also implements the optical combiner/multiplexer unit **208** using two pump combiners **502** and **504**. Each pump combiner **502** and **504** denotes any suitable pump combiner, multiplexer, or other structure(s) configured to combine pump powers. While

each pump combiner **502** and **504** is shown as a single component in FIG. 5, each pump combiner **502** and **504** could be implemented using multiple devices to perform the desired combining function.

[0061] In this example, the pump combiner **504** receives the remnant of the pump power from the optical path **202a** and pump powers from a subset of the remaining optical paths **202b-202n**. The pump combiner **502** receives pump powers from another subset of the remaining optical paths **202b-202n**. The pump combiner **502** feeds pump power(s) to the optical multiplexer **216**, while the pump combiner **504** feeds pump power(s) to the optical multiplexer **214**.

[0062] As can be seen here, FIGS. 4 and 5 indicate that different pump powers from different optical paths **202b-202n** can be combined in different ways and provided to the optical multiplexers **214** and **216**. FIGS. 4 and 5 also indicate that the remnant of the pump power from the optical path **202a** can be provided to either of the optical multiplexers **214** and **216**. In this way, the ROPA architectures **400** and **500** support both wavelength and spatial multiplexing of the pump powers.

[0063] It should be noted that the multiplexers and the connections to the multiplexers in FIGS. 4 and 5 are for illustration only and that at least three pump powers can be combined and provided to multiple locations within a forward ROPA in any other suitable manner. For example, assume only three pump powers  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  are received in FIG. 4. In such a case, the pump combiner **404** could be omitted, the pump power  $\lambda_3$  could be provided directly to the optical multiplexer **214**, and the pump combiner **402** could be used to combine the remnant of the pump power  $\lambda_1$  and the pump power  $\lambda_2$  and provide the resulting power to the optical multiplexer **216**. In other words, there are a wide variety of ways in which at least some of three or more optical pump powers can be combined (wavelength multiplexed) and provided to different locations (spatially multiplexed).

[0064] As shown in FIG. 6, a backward ROPA architecture **600** includes various components **302a-302n**, **304**, **306**, **310**, **312**, **314**, **316**, **318** described above with respect to FIG. 3. The backward ROPA architecture **600** also implements the optical combiner/multiplexer unit **308** using two pump combiners **602** and **604**. Each pump combiner **602** and **604** denotes any suitable pump combiner, multiplexer, or other structure(s) configured to combine pump powers. While each pump combiner **602** and **604** is shown as a single component in FIG. 6, each pump combiner **602** and **604** could be implemented using multiple devices to perform the desired combining function.

[0065] In this example, the pump combiner **602** receives the remnant of the pump power from the optical path **302a** and pump powers from a subset of the remaining optical paths **302b-302n**. The pump combiner **604** receives pump powers from another subset of the remaining optical paths **302b-302n**. The pump combiner **604** feeds pump power(s) to the optical multiplexer **314**, while the pump combiner **602** feeds pump power(s) to the optical multiplexer **316**.

[0066] As shown in FIG. 7, a backward ROPA architecture **700** includes various components **302a-302n**, **304**, **306**, **310**, **312**, **314**, **316**, **318** described above with respect to FIG. 3. The backward ROPA architecture **700** also implements the optical combiner/multiplexer unit **308** using two pump combiners **702** and **704**. Each pump combiner **702** and **704** denotes any suitable pump combiner, multiplexer, or other

structure(s) configured to combine pump powers. While each pump combiner **702** and **704** is shown as a single component in FIG. 7, each pump combiner **702** and **704** could be implemented using multiple devices to perform the desired combining function.

[0067] In this example, the pump combiner **704** receives the remnant of the pump power from the optical path **302a** and pump powers from a subset of the remaining optical paths **302b-302n**. The pump combiner **702** receives pump powers from another subset of the remaining optical paths **302b-302n**. The pump combiner **702** feeds pump power(s) to the optical multiplexer **316**, while the pump combiner **704** feeds pump power(s) to the optical multiplexer **314**.

[0068] As can be seen here, FIGS. 6 and 7 indicate that different pump powers from different optical paths **302b-302n** can be combined in different ways and provided to the optical multiplexers **314** and **316**. FIGS. 6 and 7 also indicate that the remnant of the pump power from the optical path **302a** can be provided to either of the optical multiplexers **314** and **316**. In this way, the ROPA architectures **600** and **700** support both wavelength and spatial multiplexing of the pump powers.

[0069] Again, it should be noted that the multiplexers and the connections to the multiplexers in FIGS. 6 and 7 are for illustration only and that at least three pump powers can be combined and provided to multiple locations within a backward ROPA in any other suitable manner. There are a wide variety of ways in which at least some of three or more optical pump powers can be combined (wavelength multiplexed) and provided to different locations (spatially multiplexed).

[0070] Although FIGS. 4 through 7 illustrate specific examples of architectures of ROPAs for use in optical transmission systems, various changes may be made to FIGS. 4 through 7. For example, the numbers of optical paths carrying pump powers can vary as needed or desired. Also, the numbers of inputs and outputs of the various optical combiner/multiplexer units can vary as needed or desired.

[0071] FIGS. 8 and 9 illustrate example multi-stage architectures of ROPAs for use in optical transmission systems according to this disclosure. For ease of explanation, the ROPA architectures in FIGS. 8 and 9 may be described as operating in the optical transmission system **100** of FIG. 1. However, these ROPA architectures could be used in any other suitable system.

[0072] As shown in FIG. 8, a forward ROPA architecture **800** includes optical paths **802a-802n**, which may be the same as or similar to the optical paths **202a-202n** in FIG. 2. The ROPA architecture **800** also includes multiple amplification stages formed by bypass hybrid filters **804a-804b** and fiber amplifiers **806a-806b**. Each of the bypass hybrid filters **804a-804b** could be the same as or similar to the bypass hybrid filter **204** in FIG. 2, and each of the fiber amplifiers **806a-806b** could be the same as or similar to the fiber amplifier **206** in FIG. 2. Each of the bypass hybrid filters **804a-804b** includes an optical demultiplexer **810a-810b**, an optical isolator **812a-812b**, and an optical multiplexer **814a-814b**, which could be the same as or similar to the corresponding components **210**, **212**, **214** in FIG. 2. An additional optical multiplexer **816** follows the second stage of amplification in FIG. 8 and generates output signals on an optical path **818**.

[0073] An optical combiner/multiplexer unit **808** operates to redirect and selectively combine the pump powers from the optical paths **802a-802n** and to provide the pump powers to the optical multiplexers **814a**, **814b**, and **816** and to the optical demultiplexer **810b**. The optical combiner/multiplexer unit **808** provides both wavelength and spatial multiplexing of the pump powers in this manner. The optical combiner/multiplexer unit **808** can be coupled to each of the components **810b**, **814a**, **814b**, and **816** via an optical fiber.

[0074] Each of the locations where the optical combiner/multiplexer unit **808** can provide pump powers (to the components **810b**, **814a**, **814b**, and **816** in this example) may be referred to as a port. The optical combiner/multiplexer unit **808** therefore provides spatial and wavelength multiplexing between its three input optical fibers and the four ports. In some embodiments, two or four of the ports could receive pump powers from the optical combiner/multiplexer unit **808**. If only two of the ports receive pump powers, the optical combiner/multiplexer unit **808** could create a bypass between the optical demultiplexer **810b** and the optical multiplexer **814b** so that pump powers are supplied only to the optical multiplexers **814a** and **816**. If four of the ports receive pump powers from the optical combiner/multiplexer unit **808**, the optical combiner/multiplexer unit **808** can provide any suitable combinations of pump powers to the optical multiplexers **814a**, **814b**, and **816** and the optical demultiplexer **810b**.

[0075] As shown in FIG. 9, a backward ROPA architecture **900** includes optical paths **902a-902n**, which may be the same as or similar to the optical paths **302a-302n** in FIG. 3. The ROPA architecture **900** also includes multiple amplification stages formed by bypass hybrid filters **904a-904b** and fiber amplifiers **906a-906b**. Each of the bypass hybrid filters **904a-904b** could be the same as or similar to the bypass hybrid filter **304** in FIG. 3, and each of the fiber amplifiers **906a-906b** could be the same as or similar to the fiber amplifier **306** in FIG. 3. Each of the bypass hybrid filters **904a-904b** includes an optical demultiplexer **910a-910b**, an optical isolator **912a-912b**, and an optical multiplexer **914a-914b**, which could be the same as or similar to the corresponding components **310**, **312**, **314** in FIG. 3. An additional optical multiplexer **916** precedes the amplification stages in FIG. 9 and receives optical signals on an optical path **918**.

[0076] An optical combiner/multiplexer unit **908** operates to redirect and selectively combine the pump powers from the optical paths **902a-902n** and to provide the pump powers to the optical multiplexers **914a**, **914b**, and **916** and to the optical demultiplexer **910b**. The optical combiner/multiplexer unit **908** provides both wavelength and spatial multiplexing of the pump powers in this manner. The optical combiner/multiplexer unit **908** can be coupled to each of the components **910b**, **914a**, **914b**, and **916** via an optical fiber.

[0077] Each of the locations where the optical combiner/multiplexer unit **908** can provide pump powers (to the components **910b**, **914a**, **914b**, and **916** in this example) may be referred to as a port. The optical combiner/multiplexer unit **908** therefore provides spatial and wavelength multiplexing between its three input optical fibers and the four ports. In some embodiments, two or four of the ports could receive pump powers from the optical combiner/multiplexer unit **908**. If only two of the ports receive pump powers, the optical combiner/multiplexer unit **908** could create a bypass between the optical demultiplexer **910b** and the optical multiplexer **914b** so that pump powers are supplied only to

the optical multiplexers **914a** and **916**. If four of the ports receive pump powers from the optical combiner/multiplexer unit **908**, the optical combiner/multiplexer unit **908** can provide any suitable combinations of pump powers to the optical multiplexers **914a**, **914b**, and **916** and the optical demultiplexer **910b**.

[0078] As can be seen here, the ability to duplicate the amplification stages in a ROPA increases the number of locations where pump powers can be injected into the ROPA. As a result, this approach provides greater flexibility in allowing pump powers to be combined and used to amplify optical signals in the ROPA.

[0079] Although FIGS. 8 and 9 illustrate examples of multi-stage architectures **800** and **900** of ROPAs for use in optical transmission systems, various changes may be made to FIGS. 8 and 9. For example, each ROPA could include more than two amplification stages. Also, the numbers of optical paths carrying pump powers can vary as needed or desired. In addition, the numbers of inputs and outputs of the various optical combiner/multiplexer units can vary as needed or desired.

[0080] FIGS. 10 through 12 illustrate a specific example of an optical transmission system **1000** and related ROPAs according to this disclosure. The optical transmission system **1000** in this example denotes an ultra-long unrepeated system that can achieve transmissions over 600 kilometers at 10 gigabits per second (10 G) or 100 gigabits per second (100 G). While the optical transmission system **1000** shown in FIG. 10 is a unidirectional link, the same structure could be replicated to create a bi-directional link or multiple bi-directional links.

[0081] As shown in FIG. 10, a line card **1002** denotes an optical transmitter, such as a 10 G or 100 G line card. An Erbium-doped fiber amplifier (EDFA) **1004** amplifies the optical signals from the line card **1002**, and a Dispersion Compensation Unit (DCU) **1006** is used with the EDFA **1004**. A Wavelength Selective Switch (WSS) **1008** follows the EDFA **1004**. Pump sources **1010a-1010n** generate pump powers, which are provided over optical fibers **1012a-1012n** to a forward ROPA **1014**. An optical fiber **1016** couples the forward ROPA **1014** to a backward ROPA **1018**. Pump sources **1020a-1020n** generate pump powers, which are provided over optical fibers **1022a-1022n** to the backward ROPA **1018**. An EDFA **1024** amplifies optical signals from the backward ROPA **1018**, and a WSS **1026** follows the EDFA **1024**. A line card **1028** denotes an optical receiver, such as a 10 G or 100 G line card.

[0082] A particular implementation of the system **1000** can have the following characteristics, although these details are for illustration only. The line card **1002** can be configured to transmit 100 G at 1563.86 nm or 10 G at 1563.05 nm. A 100 G signal can be NRZ-PM-QPSK modulated at 120 gigabits per second, which accounts for a 15% overhead for a Soft-Decision Forward Error Correction (SD-FEC) code. The SD-FEC can correct a bit error rate (BER) of  $1.9 \times 10^{-2}$  to less than  $10^{-15}$  (NCG of 11.1 dB). A 10 G channel can operate at 12.5 gigabits per second, which includes a 25% overhead for an Ultra FEC (FEC threshold is  $9.5 \times 10^{-3}$ ). The optical signal is amplified through a double-stage EDFA **1004** with a mid-stage DCU **1006**, followed by a WSS **1008** (such as a 100 GHz WSS) to filter out amplified spontaneous emission (ASE) from the transmit EDFA **1004**. At the receive end, an EDFA **1024** amplifies the received signal, and another WSS **1026** is used to demultiplex the channels.

For 10 G operation, the components within a box **1030** (two EDFAs and multiple DCUs) can be used in place of the EDFA **1024** to provide optical dispersion compensation. At the transmit side, approximately  $-1,600$  ps/nm of dispersion pre-compensation can be placed in the mid-stage of the EDFA **1004** to improve transmission performance for both 100 G and 10 G transmissions. Approximately  $-11,000$  ps/nm dispersion post-compensation at the receiver side can be used for 10 G transmissions.

**[0083]** The span formed by the optical fiber **1016** can be assembled with CORNING VASCADE EX2000 optical fiber. The EX2000 fiber is a G.654B fiber (a cutoff-shifted single-mode fiber with a cutoff wavelength  $\leq 1530$  nm) with a chromatic dispersion of  $\leq 20.2$  ps/nm-km and a large  $A_{err}$  of  $112 \mu\text{m}^2$ , enabling high optical launch powers into the fiber.

**[0084]** In the signal path, the forward ROPA **1014** and the backward ROPA **1018** are located at 128.0 km and 151.4 km, respectively, from the end-points or terminals. For 100 G transmissions, the distance between the ROPAs can be adjusted to 327.6 km for a total span length of 607.0 km and a span loss of 97.2 dB (losses of the ROPAs not included), resulting in an average fiber loss of 0.160 dB/km (including splices and connectors). For 10 G transmissions, the total distance can be increased to 632.0 km (352.6 km between ROPAs) for a span loss of 101.0 dB.

**[0085]** For the dedicated pump paths, fiber lengths of 128.2 km and 128.7 km can be used in pump paths for the forward ROPA, and fiber lengths of 154.2 km and 151.7 km can be used in pump paths for the backward ROPA. Distributed Raman pumps can use a common commercial Raman pump module (NU-WAVE OPTIMA SE24), each of which supports five pump wavelengths distributed in the range between 1420 nm and 1500 nm. However, the Raman pump modules in the signal path may not use the pump at the longest wavelength, so those pump modules operate with four pump wavelengths in the range between 1420 and 1480 nm. Turning off the longest pump wavelength (with less “walkoff” between pump and signal in a dispersive fiber) helps to reduce the relative intensity noise (RIN) transfer penalty in the forward direction and provides more efficient Raman gain to the signal wavelength around 1563 nm. The pump modules in the pump paths can use all five pump wavelengths. Due to the Raman interaction between the pump wavelengths along the fiber, the longest wavelength in both the forward and backward pump modules can have the highest power at the ROPA and can primarily be used to excite the Erbium fibers.

**[0086]** FIG. 11 illustrates one example implementation of the forward ROPA **1014** in the system **1000** of FIG. 10. As shown in FIG. 11, the forward ROPA **1014** includes optical paths **1102a-1102c**, a bypass hybrid filter **1104**, and a fiber amplifier **1106** (such as a 20 m Erbium fiber). The bypass hybrid filter **1104** includes an optical demultiplexer **1110**, an optical isolator **1112**, and an optical multiplexer **1114**. There is an additional optical multiplexer **1116** following the fiber amplifier **1106**, which generates output signals on an optical path **1118**. An optical combiner/multiplexer unit here is implemented using the optical path **1102c** and an optical multiplexer **1120**. Pump power on the optical path **1102c** is provided directly to the optical multiplexer **1114**. Remnant pump power from the optical path **1102a** and pump power on the optical path **1102b** are provided to the optical multiplexer **1116** via the optical multiplexer **1120**.

**[0087]** FIG. 12 illustrates one example implementation of the backward ROPA **1018** in the system **1000** of FIG. 10. As shown in FIG. 12, the backward ROPA **1018** includes optical paths **1202a-1202c** and multiple amplification stages containing bypass hybrid filters **1204a-1204b** and fiber amplifiers **1206a-1206b** (such as 20 m Erbium fibers). Each of the bypass hybrid filters **1204a-1204b** includes an optical demultiplexer **1210a-1210b**, an optical isolator **1212a-1212b**, and an optical multiplexer **1214a-1214b**. There is an additional optical multiplexer **1216** preceding the fiber amplifier **1206b**, which receives signals on an optical path **1218**. An optical combiner/multiplexer unit here is implemented using the optical path **1202c** and an optical multiplexer **1220**. Pump power on the optical path **1202c** is provided directly to the optical multiplexer **1214a**. Remnant pump power from the optical path **1202a** and pump power on the optical path **1202b** are provided to the optical multiplexer **1216** via the optical multiplexer **1220**. The optical demultiplexer **1210b** and the optical multiplexer **1214b** are tied together. The hybrid filter **1204b** here splits the Erbium gain into two sections while allowing the fiber amplifiers to be excited from both directions, which can help to improve the noise figure (NF) of the backward ROPA **1018**.

**[0088]** During operation, the signal power launched into the optical link **1012a** can be  $-9.4$  dBm for 100 G and  $-3.6$  dBm for 10 G transmissions. The same distributed Raman pump powers can be used for both 100 G and 10 G transmissions, such as 1860 mW in the signal path and 2060 mW in the pump paths (the same pump powers can be used for both forward and backward pumping). The pump power reaching the EDF in the forward ROPA can be 5.2 mW from the signal path and 8.7 mW and 8.2 mW for the two pump paths. The forward ROPA gain can be 18.8 dB for 100G and 13.2 dB for 10G. At the backward ROPA, the pump power reaching the EDF can be 1.7 mW, 3.3 mW, and 2.4 mW from the signal path and the two pump paths. The backward ROPA gain could be 25.4 dB gain at 100 G and 26.2 dB at 10 G. The maximum power of the signal right after the forward ROPA at 128 km could be  $+11.9$  dBm for 100 G and  $+12.2$  dBm for 10 G. The measured OSNR at the receiver could be 13.7 dB (0.1 nm) for 100 G and 10.0 dB (0.1 nm) for 10 G, which is in good agreement with simulations (13.6 dB, 10.1 dB).

**[0089]** Using this arrangement, the average pre-FEC BER over the duration of a 45-hour BER stability test at 100 G transmission could be  $1.18 \times 10^{-2}$  (corresponding to a Q of 7.1 dB) with less than 0.3 dBQ fluctuation and no uncorrected errors after SD-FEC. The total signal propagation penalty (which includes nonlinear, RIN, and MPI penalties) could be estimated to be 0.6 dB in Q compared to back-to-back performance (Q of 7.7 dB at 13.7 dB OSNR). A 30-hour stability test at 100 G unrepeated transmission could have an average pre-FEC BER of  $7.80 \times 10^{-3}$  (corresponding to a Q of 7.8 dB) with less than 0.2 dBQ fluctuation and no uncorrected errors after Ultra FEC.

**[0090]** Although FIGS. 10 through 12 illustrate one specific example of an optical transmission system **1000** and related ROPAs **1014** and **1018**, various changes may be made to FIGS. 10 through 12. For example, specific details provided above, such as specific distances, structures, and performance values, relate to a particular implementation of the system **1000**. Any other suitable distances, structures, performance values, and other features could be used in the



system **1000**. As particular examples, each of the ROPAs **1014** and **1018** in the system **1000** could be implemented in any other ways described above.

[0091] FIG. **13** illustrates an example multi-span optical transmission system **1300** according to this disclosure. As shown in FIG. **13**, the optical transmission system **1300** includes end-points or terminals **1302** and **1304**, which could be the same as or similar to the end-points or terminals **102** and **104**. The end-points or terminals **1302** and **1304** are coupled by an optical communication link that includes multiple spans **1306a-1306n** of optical fibers and multiple ROPAs **1308a-1308m** positioned in-line with the multiple spans **1306a-1306n**.

[0092] One or more of the ROPAs **1308a-1308m** could be implemented using any of the ROPA designs described above and use at least three pump powers that are wavelength and spatially multiplexed. For example, the ROPA **1308a** closest to the end-point or terminal **1302** could receive and multiplex at least three pump powers from the end-point or terminal **1302**, and/or the ROPA **1308m** closest to the end-point or terminal **1304** could receive and multiplex at least three pump powers from the end-point or terminal **1304**. The other ROPAs between the ROPA **1308a** and the ROPA **1308m** could denote conventional ROPAs or could denote any of the ROPA designs described above (in which case each of those ROPAs would receive and multiplex at least three pump powers, such as from the closest end-point or terminal).

[0093] Although FIG. **13** illustrates one example of a multi-span optical transmission system **1300**, various changes may be made to FIG. **13**. For example, the spans **1306a-1306n** and ROPAs **1308a-1308m** here form a unidirectional link from the end-point or terminal **1302** to the end-point or terminal **1304**. The same or similar structure could be replicated and reversed to form a unidirectional link from the end-point or terminal **1304** to the end-point or terminal **1302**, thereby forming a fiber pair. Multiple fiber pairs could also be used between the end-points or terminals **1302** and **1304**.

[0094] FIG. **14** illustrates an example method **1400** for operating a ROPA in an optical transmission system according to this disclosure. For ease of explanation, the method **1400** in FIG. **14** is described as being used in the optical transmission system **100** of FIG. **1** using the ROPA architectures **200** and **300** of FIGS. **2** and **3**. However, the method **1400** could be used in any other suitable system and with any other suitable ROPA architectures, including the other systems and ROPA architectures described above.

[0095] As shown in FIG. **14**, optical signals and remnant pump power are received at a ROPA at step **1402**. This could include, for example, a forward ROPA **110** or **130** receiving optical signals and a remnant of first pump power over the same optical fiber **114a** or **134a**. This could also include a backward ROPA **112** or **132** receiving optical signals over one optical fiber **120** or **140** and a remnant of first pump power over another optical fiber **122a** or **142a**.

[0096] Additional pump powers are received at the ROPA at step **1404**. This could include, for example, the ROPA **110**, **112**, **130**, **132** receiving at least second and third pump powers over additional optical fibers **114b-114n**, **122b-122n**, **134b-134n**, **142b-142n**. In some embodiments, the ROPA receives two additional pump powers over two additional optical fibers.

[0097] The pump powers are wavelength and spatially multiplexed at step **1406**. This could include, for example, an optical combiner/multiplexer unit **208** or **308** in the ROPA **110**, **112**, **130**, **132** combining at least two of the pump powers and supplying different pump powers to different locations within the ROPA **110**, **112**, **130**, **132**. As described above, at least one of the pump powers could be provided directly to an optical multiplexer (without combination), while other pump powers could be combined prior to be provided to an optical multiplexer. However, any other suitable wavelength and spatial multiplexing could be used.

[0098] The optical signals are amplified in the ROPA using the pump powers at step **1408**. This could include, for example, one or more fiber amplifiers in one or more amplification stages of the ROPA **110**, **112**, **130**, **132** amplifying the optical signals. The fiber amplifiers can receive pump powers in the forward direction and/or the backward direction depending on how the pump powers are spatially multiplexed in the ROPA.

[0099] The amplified optical signals are output at step **1410**. This could include, for example, the forward ROPA **110** or **130** outputting the amplified optical signals over the optical fiber **120** or **140**. This could also include the backward ROPA **112** or **132** outputting the amplified optical signals over the optical fiber **122a** or **142a**.

[0100] Although FIG. **14** illustrates one example of a method **1400** for operating a ROPA in an optical transmission system, various changes may be made to FIG. **14**. For example, while shown as a series of steps, various steps in FIG. **14** could overlap, occur in parallel, occur in a different order, or occur any number of times.

[0101] Note that any suitable control mechanism could be used to control the wavelength and spatial multiplexing provided in a ROPA. The wavelength and spatial multiplexing could be set to have a specific configuration (which may or may not change over time), or the wavelength and spatial multiplexing could routinely or repeatedly change in order to accommodate changing conditions within an optical transmission system. If the wavelength and spatial multiplexing can change over time, a computing device or other control mechanism could use any suitable control logic for controlling the wavelength and spatial multiplexing in order to obtain desirable amplification results using the ROPA.

[0102] In some embodiments, various functions described in this patent document are implemented or supported by a computer program that is formed from computer readable program code and that is embodied in a computer readable medium. The phrase “computer readable program code” includes any type of computer code, including source code, object code, and executable code. The phrase “computer readable medium” includes any type of medium capable of being accessed by a computer, such as read only memory (ROM), random access memory (RAM), a hard disk drive, a compact disc (CD), a digital video disc (DVD), or any other type of memory. A “non-transitory” computer readable medium excludes wired, wireless, optical, or other communication links that transport transitory electrical or other signals. A non-transitory computer readable medium includes media where data can be permanently stored and media where data can be stored and later overwritten, such as a rewritable optical disc or an erasable memory device.

[0103] It may be advantageous to set forth definitions of certain words and phrases used throughout this patent document. The terms “application” and “program” refer to one or

more computer programs, software components, sets of instructions, procedures, functions, objects, classes, instances, related data, or a portion thereof adapted for implementation in a suitable computer code (including source code, object code, or executable code). The terms “transmit,” “receive,” and “communicate,” as well as derivatives thereof, encompasses both direct and indirect communication. The terms “include” and “comprise,” as well as derivatives thereof, mean inclusion without limitation. The term “or” is inclusive, meaning and/or. The phrase “associated with,” as well as derivatives thereof, may mean to include, be included within, interconnect with, contain, be contained within, connect to or with, couple to or with, be communicable with, cooperate with, interleave, juxtapose, be proximate to, be bound to or with, have, have a property of, have a relationship to or with, or the like. The phrase “at least one of,” when used with a list of items, means that different combinations of one or more of the listed items may be used, and only one item in the list may be needed. For example, “at least one of: A, B, and C” includes any of the following combinations: A, B, C, A and B, A and C, B and C, and A and B and C.

**[0104]** The description in the present application should not be read as implying that any particular element, step, or function is an essential or critical element that must be included in the claim scope. The scope of patented subject matter is defined only by the allowed claims. Moreover, none of the claims invokes 35 U.S.C. §112(f) with respect to any of the appended claims or claim elements unless the exact words “means for” or “step for” are explicitly used in the particular claim, followed by a participle phrase identifying a function. Use of terms such as (but not limited to) “mechanism,” “module,” “device,” “unit,” “component,” “element,” “member,” “apparatus,” “machine,” “system,” “processor,” or “controller” within a claim is understood and intended to refer to structures known to those skilled in the relevant art, as further modified or enhanced by the features of the claims themselves, and is not intended to invoke 35 U.S.C. §112(f).

**[0105]** While this disclosure has described certain embodiments and generally associated methods, alterations and permutations of these embodiments and methods will be apparent to those skilled in the art. Accordingly, the above description of example embodiments does not define or constrain this disclosure. Other changes, substitutions, and alterations are also possible without departing from the scope of the invention as defined by the following claims.

1.-22. (canceled)

**23.** An apparatus comprising:

a remote optically pumped amplifier (ROPA) comprising:  
 a bypass filter configured to receive and separate an optical signal and first pump power;  
 an amplifier configured to amplify the optical signal; and  
 an optical combiner/multiplexer configured to (i) receive multiple pump powers including the first pump power and (ii) provide different pump powers or combinations of pump powers to different locations within the ROPA to feed the amplifier.

**24.** The apparatus of claim 23, wherein:

the bypass filter comprises a first optical multiplexer optically coupled to a first side of the amplifier, the first optical multiplexer configured to feed at least one of the pump powers to the amplifier in a first direction; and

the ROPA further comprises a second optical multiplexer optically coupled to a second side of the amplifier, the second optical multiplexer configured to feed at least one other of the pump powers to the amplifier in a second direction.

**25.** The apparatus of claim 24, wherein the optical combiner/multiplexer is configured to provide at least one of the pump powers to one of the optical multiplexers without combination with any other pump powers.

**26.** The apparatus of claim 23, wherein the optical combiner/multiplexer is configured to wavelength multiplex and spatially multiplex the pump powers.

**27.** The apparatus of claim 23, wherein the bypass filter comprises:

an optical demultiplexer configured to separate the optical signal and the first pump power;  
 an optical multiplexer configured to combine the optical signal and at least one of the pump powers, the optical multiplexer optically coupled to the amplifier; and  
 an optical isolator configured to isolate the first pump power from the optical multiplexer.

**28.** The apparatus of claim 23, wherein the optical combiner/multiplexer comprises multiple pump combiners each configured to combine at least two of the pump powers.

**29.** The apparatus of claim 23, wherein the ROPA comprises a forward ROPA configured to receive the optical signal and the first pump power over a common optical fiber.

**30.** The apparatus of claim 23, wherein the ROPA comprises a backward ROPA configured to receive the optical signal over a first optical fiber and to receive the first pump power over a second optical fiber.

**31.** The apparatus of claim 23, wherein:

the ROPA comprises a multi-stage ROPA;  
 one stage of the multi-stage ROPA comprises the bypass filter and the amplifier; and  
 at least one additional stage of the multi-stage ROPA comprises at least one additional bypass filter and at least one additional amplifier.

**32.** A system comprising:

an optical communication link comprising a remote optically pumped amplifier (ROPA), the ROPA comprising:  
 a bypass filter configured to receive and separate an optical signal and first pump power;  
 an amplifier configured to amplify the optical signal; and  
 an optical combiner/multiplexer configured to (i) receive multiple pump powers including the first pump power and (ii) provide different pump powers or combinations of pump powers to different locations within the ROPA to feed the amplifier.

**33.** The system of claim 32, wherein:

the bypass filter comprises a first optical multiplexer optically coupled to a first side of the amplifier, the first optical multiplexer configured to feed at least one of the pump powers to the amplifier in a first direction; and  
 the ROPA further comprises a second optical multiplexer optically coupled to a second side of the amplifier, the second optical multiplexer configured to feed at least one other of the pump powers to the amplifier in a second direction.

**34.** The system of claim 32, wherein the optical combiner/multiplexer is configured to wavelength multiplex and spatially multiplex the pump powers.

**35.** The system of claim **32**, wherein the bypass filter comprises:

an optical demultiplexer configured to separate the optical signal and the first pump power;  
an optical multiplexer configured to combine the optical signal and at least one of the pump powers, the optical multiplexer optically coupled to the amplifier; and  
an optical isolator configured to isolate the first pump power from the optical multiplexer.

**36.** The system of claim **32**, wherein:  
the ROPA comprises a backward ROPA; and  
the optical communication link further comprises a forward ROPA and an optical fiber coupling the forward ROPA and the backward ROPA.

**37.** The system of claim **36**, wherein the optical communication link comprises one of a pair of optical communication links, another of the optical communication links comprising another forward ROPA and another backward ROPA.

**38.** A method comprising:  
receiving an optical signal and multiple pump powers including a first pump power at a remote optically pumped amplifier (ROPA);

providing the optical signal to an amplifier of the ROPA for amplification; and

providing different pump powers or combinations of pump powers to different locations within the ROPA to feed the amplifier.

**39.** The method of claim **38**, wherein the first pump power represents a remnant of pump power used for Raman amplification of the optical signal.

**40.** The method of claim **38**, wherein providing different pump powers or combinations of pump powers to different locations within the ROPA comprises:

feeding at least one of the pump powers to the amplifier in a first direction; and

feeding at least one other of the pump powers to the amplifier in a second direction.

**41.** The method of claim **38**, wherein providing different pump powers or combinations of pump powers to different locations within the ROPA comprises wavelength multiplexing and spatially multiplexing the pump powers.

**42.** The method of claim **38**, wherein the ROPA comprises a ROPA in a multi-span optical communication link.

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