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Kerfoot, III et al.

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(54) **WIDE BANDWIDTH RAMAN AMPLIFIER EMPLOYING A PUMP UNIT GENERATING A PLURALITY OF WAVELENGTHS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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This patent is subject to a terminal disclaimer.

Primary Examiner—John D. Lee

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(57) **ABSTRACT**

(22) Filed: **Feb. 26, 1998**

A Raman amplifier is provided that includes at least a portion of optical fiber in which an optical signal travels. The optical fiber portion may encompass all or part of the optical transmission path of an optical communication system. A pump energy unit is provided that includes first and second pump sources providing pump power at first and second wavelengths, respectively. The first and second wavelengths generate first and second gain profiles in the optical fiber portion. The first and second gain profiles overlap in wavelength. An optical coupler couples the pump power to the optical fiber portion. Since the gain profiles overlap, the Raman amplifier has a greater bandwidth than can be achieved with a pump operating at a single wavelength.

(51) **Int. Cl.⁷** **H01S 3/30**

(52) **U.S. Cl.** **372/3; 359/334; 385/15; 385/27**

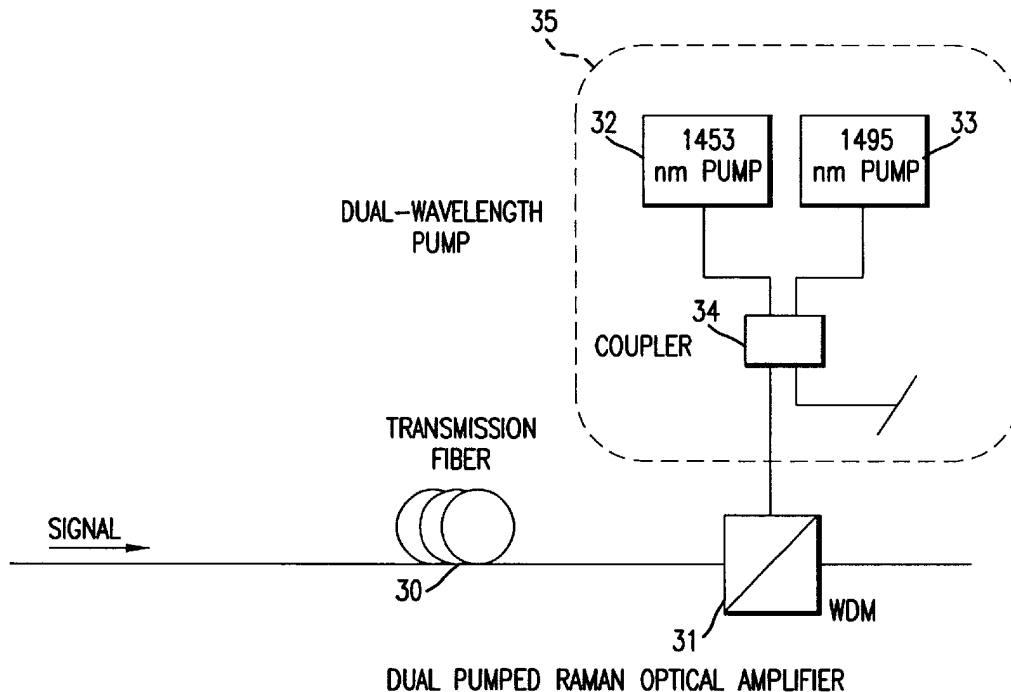
(58) **Field of Search** **359/334; 372/3, 372/6, 23; 385/15, 27**

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14 Claims, 6 Drawing Sheets



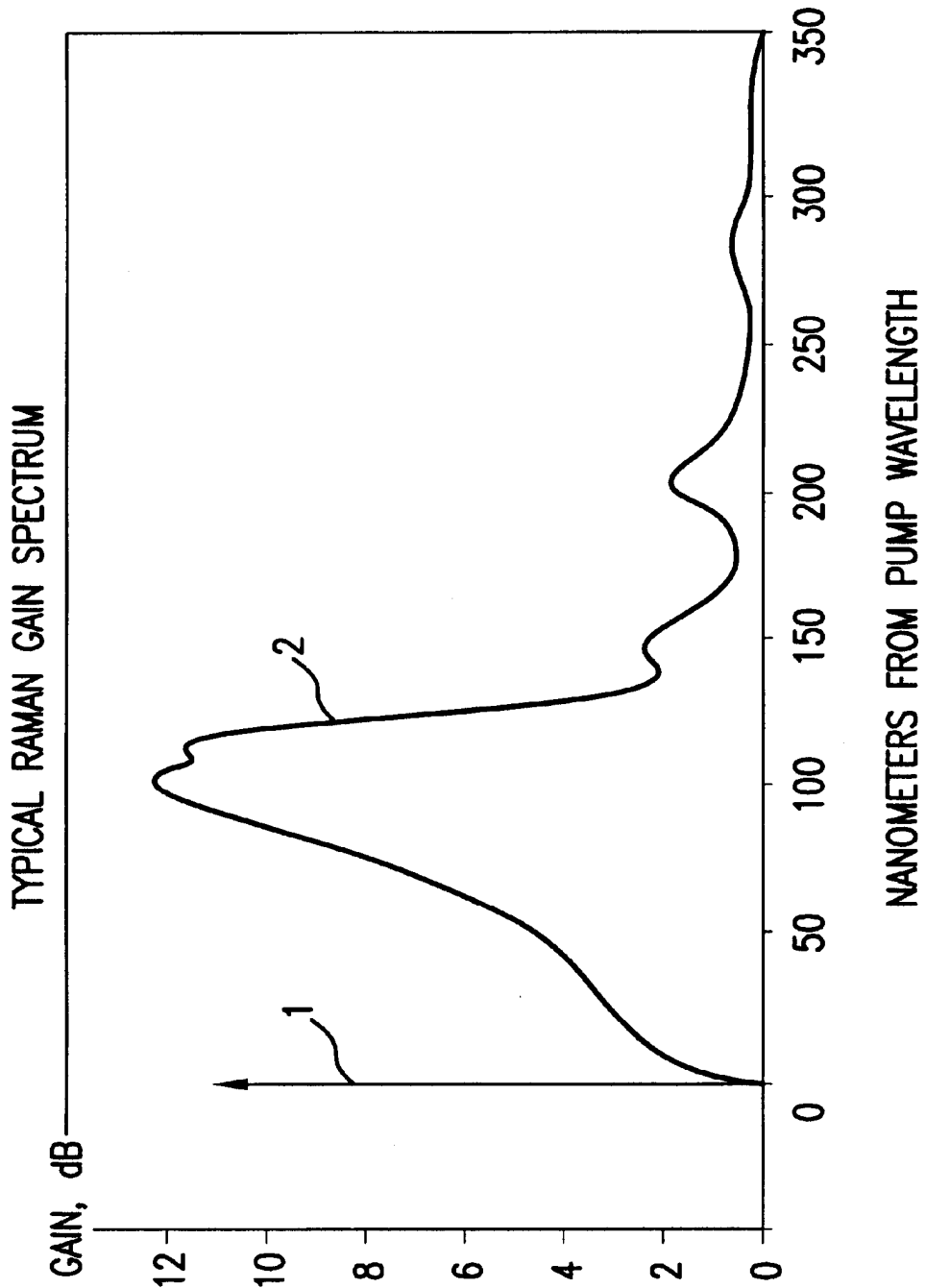


FIG.1

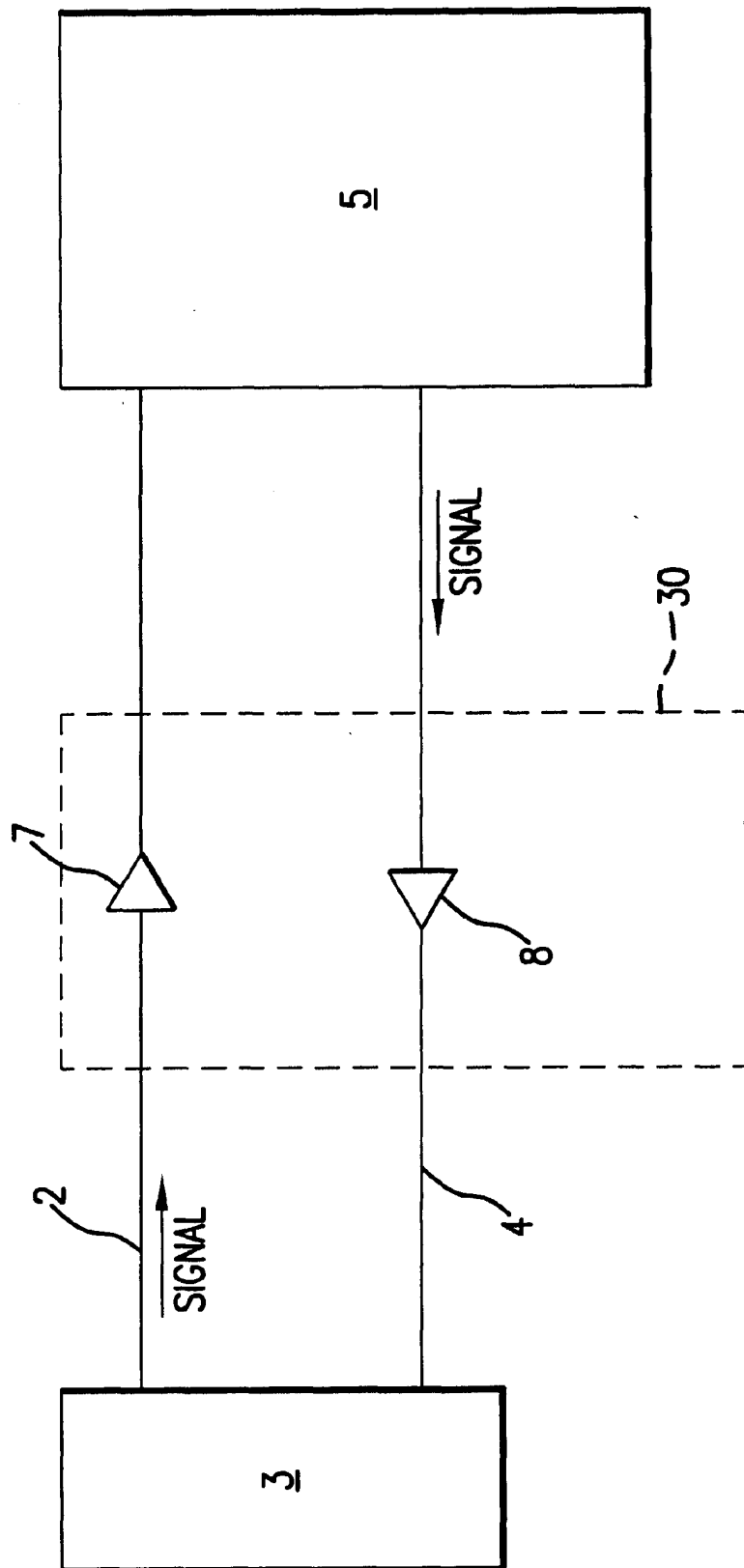
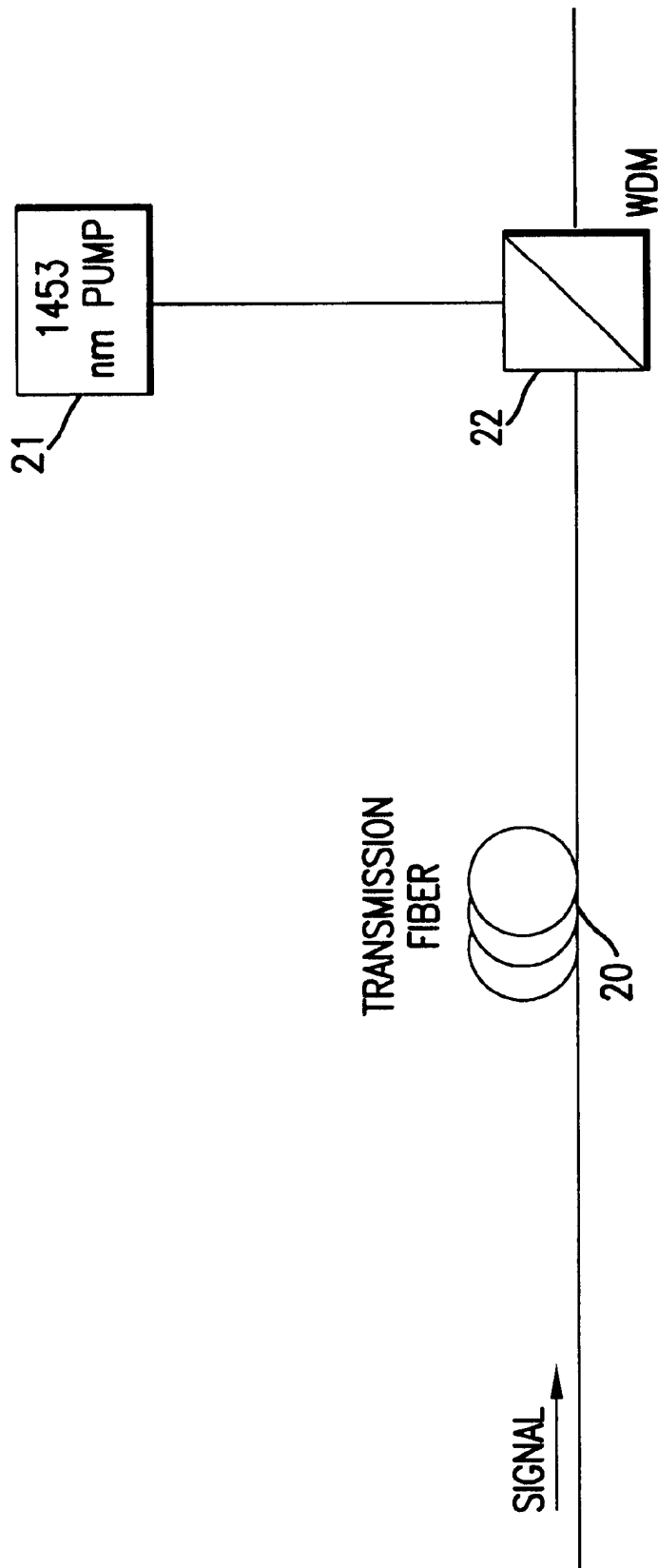
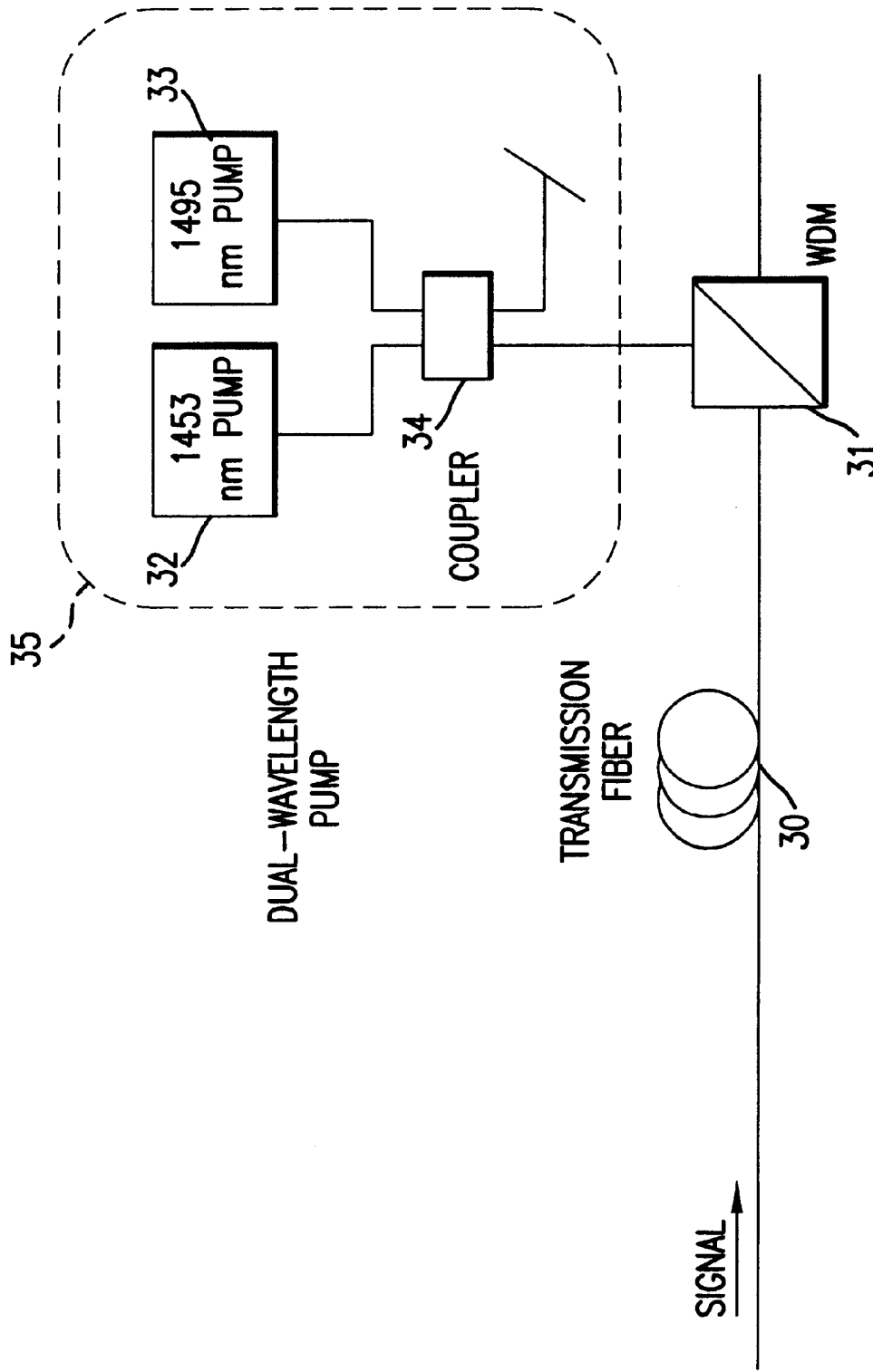


FIG.2



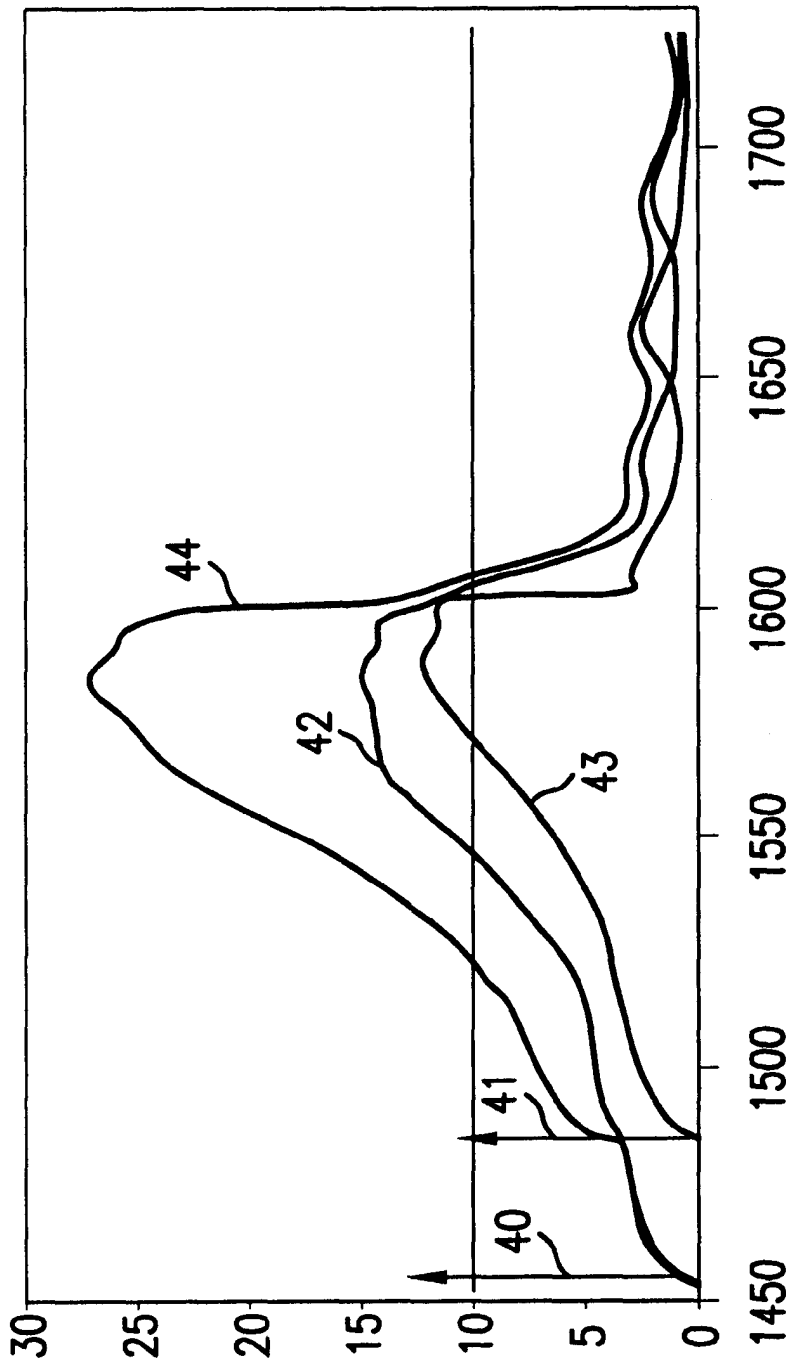
BASIC RAMAN OPTICAL AMPLIFIER

FIG.3



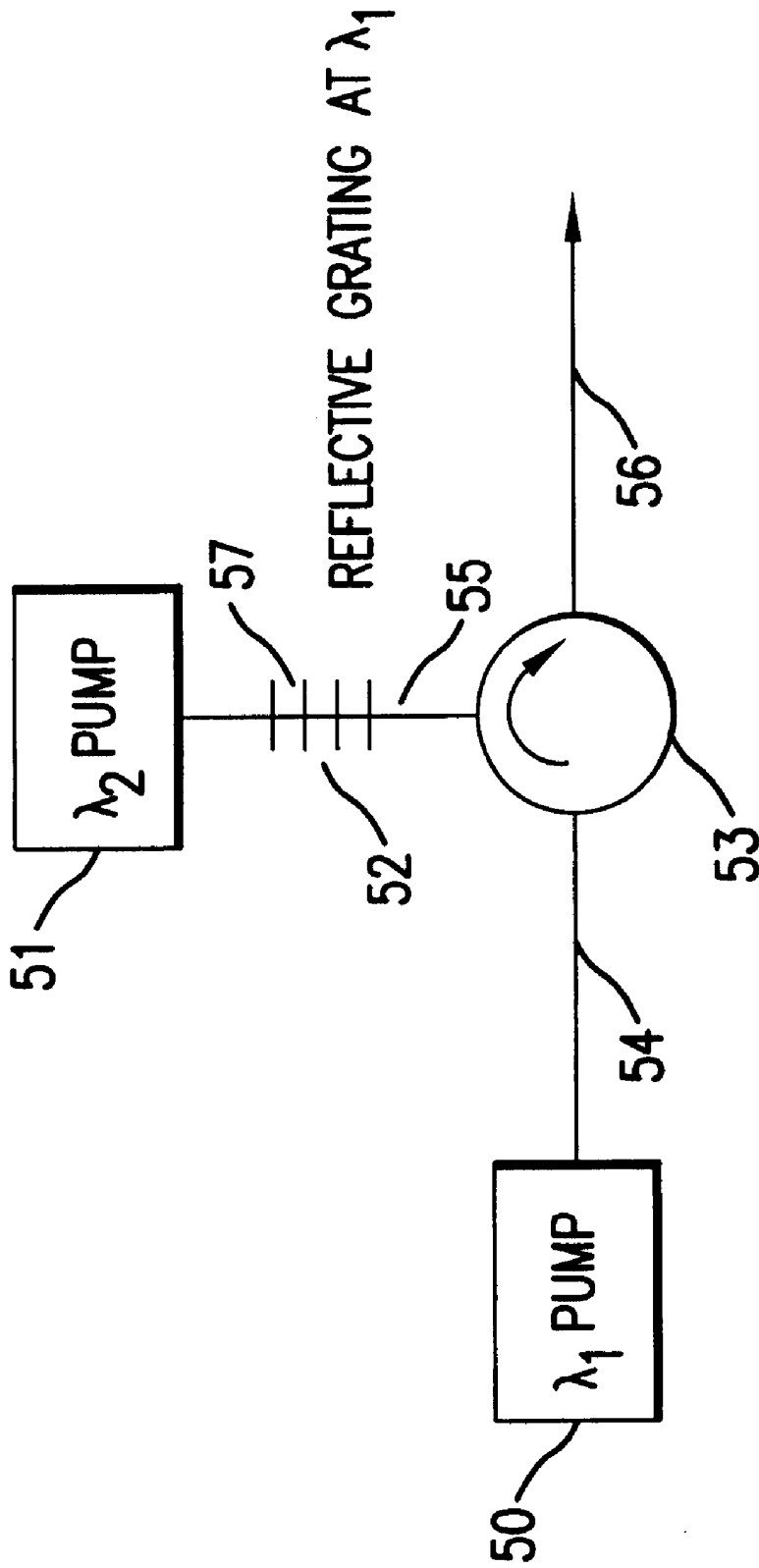
DUAL PUMPED RAMAN OPTICAL AMPLIFIER

FIG. 4



TYPICAL RAMAN SPECTRUM RESULTING FROM TWO OPTICAL PUMPS

FIG.5



ALTERNATE MEANS FOR COMBINING PUMPS

FIG.6

WIDE BANDWIDTH RAMAN AMPLIFIER EMPLOYING A PUMP UNIT GENERATING A PLURALITY OF WAVELENGTHS

FIELD OF THE INVENTION

The present invention relates generally to optical amplifiers, and more particularly to a Raman amplifier having a relatively wide gain profile.

BACKGROUND OF THE INVENTION

Broad bandwidth optical transmission systems have received a great deal of attention in recent years. Such systems require broad bandwidth optical amplifiers to achieve transmission of high capacity wavelength division multiplexed signals. A type of optical amplifier that is commonly employed incorporates rare-earth doped optical fibers as the gain medium. In particular, the rare-earth material that is often selected is erbium. Rare-earth doped optical fiber amplifiers are often referred to as discrete or lumped amplifiers, in contrast to so-called distributed amplifiers in which signal amplification occurs along the signal transmission path. An example of a distributed amplifier is a Raman amplifier.

Raman amplification is accomplished by introducing the signal and pump energies along the same optical fiber. The pump and signal may be copropagating or counterpropagating with respect to one another. A Raman amplifier uses stimulated Raman scattering, which occurs in silica fibers when an intense pump beam propagates through it. Stimulated Raman scattering is an inelastic scattering process in which an incident pump photon loses its energy to create another photon of reduced energy at a lower frequency. The remaining energy is absorbed by the fiber medium in the form of molecular vibrations (i.e., optical phonons). That is, pump energy of a given wavelength amplifies a signal at a longer wavelength. The relationship between the pump energy and the Raman gain for a silica fiber is shown in FIG. 1. The particular wavelength of the pump energy that is used in this example is denoted by reference numeral 1. As shown, the gain spectrum 2 for this particular pump wavelength is shifted in wavelength with respect to the pump wavelength.

The Raman gain spectrum in a lossless transmission fiber, as graphically illustrated in FIG. 1, may be expressed as follows:

$$G(\lambda) = e^{g_r(\lambda)PL/A} \quad (1)$$

where P is the optical pump power, L/A is the effective length divided by the effective cross-sectional area of the pump beam inside the fiber, and $g_r(\lambda)$ is the Raman gain coefficient, which is dependent on the material properties of the particular transmission fiber that is employed.

As FIG. 1 indicates, the bandwidth of the Raman amplifier is limited. For example, the bandwidth of the amplifier shown in FIG. 1 is only about 20 nm at 10 dB. Moreover, while much attention has been focused on expanding the bandwidth of rare-earth doped optical amplifiers, such a result has been difficult to achieve because of the properties of rare-earth doped fibers.

Accordingly, it would be desirable to provide an optical amplifier that has a gain profile with a wider bandwidth than is currently available from rare-earth doped fiber amplifiers and Raman amplifiers.

SUMMARY OF THE INVENTION

In accordance with the present invention, a Raman amplifier is provided that includes at least a portion of optical fiber

in which an optical signal travels. The optical fiber portion may encompass all or part of the optical transmission path of an optical communication system. A pump energy unit is provided that includes first and second pump sources providing pump power at first and second wavelengths, respectively. The first and second wavelengths generate first and second gain profiles in the optical fiber portion. The first and second gain profiles overlap in wavelength. An optical coupler couples the pump power to the optical fiber portion. Since the gain profiles overlap, the Raman amplifier has a greater bandwidth than can be achieved with a pump operating at a single wavelength.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows the relationship between pump energy and Raman gain for a silica fiber.

FIG. 2 shows an optical communication system that employs optical amplifiers.

FIG. 3 shows the pertinent details of a known Raman amplifier.

FIG. 4 shows a Raman amplifier constructed in accordance with the present invention.

FIG. 5 shows the Raman gain provided by the amplifier shown in FIG. 4.

FIG. 6 shows the pertinent details of an alternative embodiment of the invention.

DETAILED DESCRIPTION

Referring to FIG. 2, there is disclosed a conventional lightwave communication system which utilizes lumped optical fiber amplifiers such as rare-earth doped fiber amplifiers. The system includes transmitter/receiver terminals 3 and 5 and optical transmission fiber paths 2 and 4 supporting bi-directional communication. The signals being transmitted from the terminals 3 and 5 are in optical form. There is no intermediate conversion to electrical form. A plurality of lumped optical amplifiers 7 and 8 are interposed in the fiber paths 2 and 4 between the transmitter/receiver terminals 3 and 5. Optical amplifiers 7 and 8 contain a length of fiber that provides a gain medium, an energy source that pumps the fiber to provide gain, and a means of coupling the pump energy into the fiber without interfering with the signal being amplified. These components of the optical amplifiers are shown in greater detail in FIG. 3, in which the lumped optical amplifier is replaced with a distributed optical amplifier. While only one pair of optical amplifiers is depicted in FIG. 2 for clarity of discussion, it should be understood by those skilled in the art that the present invention finds application in transmission paths of all lengths having many additional pairs of optical amplifiers.

Referring to FIG. 3, each distributed optical amplifier includes an optical fiber portion 20 of the transmission path in which Raman gain is to be generated. This portion 20 of fiber may vary in size and may be limited, for example, to a small section of the transmission path. Alternatively, the fiber portion 20 in which Raman gain is generated may have a length encompassing the entire transmission path. The fiber portion 20 is coupled to a source of optical pump energy 21 via a coupler 22 such as a wavelength division multiplexer (WDM).

FIG. 4 shows a Raman amplifier 100 constructed in accordance with the present invention. Pairs of Raman amplifiers 100 may be used in a transmission system such as shown in FIG. 2. Similar to FIG. 3, the Raman amplifier 100 includes optical fiber portion 30 in which Raman gain is

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generated and an optical pump unit **35** coupled to the fiber portion **30** by an optical coupler **31**. In accordance with the present invention, the pump unit **35** includes first and second optical pump sources **32** and **33**. An optical coupler **34** combines the energy from pump sources **32** and **33** and directs the resulting beam to optical coupler **31**, which as previously noted may be a WDM coupler. As explained below, the pump sources **32** and **33** generate pump energy at different wavelengths selected to maximize the amplifier bandwidth.

The gain spectrum resulting from a two-wavelength pump source such as shown in FIG. **4** is approximately given by:

$$G(\lambda) = e^{g_r(\lambda-\lambda_1)P_1L/A + g_r(\lambda-\lambda_2)P_2L/A} \quad (2)$$

where g_r is the Raman gain coefficient for the particular fiber material in which the gain is generated, $g_r(\lambda-\lambda_1)$ is the Raman gain coefficient arising from the first pump source **32** providing energy at a wavelength λ_1 and power P_1 and $g_r(\lambda-\lambda_2)$ is the Raman gain coefficient arising from the second pump source **33** providing energy at a wavelength λ_2 and power P_2 . In one embodiment of the invention, pump source **32** provides pump energy at 1455 nm and pump source **33** provides pump energy at 1495 nm to amplify a WDM signal centered at about 1560 nm.

FIG. **5** shows the Raman gain provided by each of the pumps **32** and **33** individually and collectively. The pump energy provided by pump source **32** is denoted by reference numeral **40** and the pump energy provided by pump source **33** is denoted by reference numeral **41**. The pump energies **40** and **41** generate in the transmission fiber gain spectra **42** and **43**, respectively. In both cases the gain becomes substantial at a wavelength about 100 nm greater than each respective pump wavelength.

Composite gain spectrum **44** represents the addition of gain spectra **42** and **43**. Gain spectrum **44** is derived from (2) above. As is evident from FIG. **5**, one advantage of the present invention is that the bandwidth of the gain (measured at 10 dB) is substantially greater for composite gain spectrum **44** than for the individual gain spectra **42** and **43**. Accordingly, by providing two pump sources operating at different wavelengths, the inventive amplifier has a wide bandwidth more suitable than discrete erbium doped amplifiers for use in optical transmission systems.

In an alternative embodiment of the invention, the coupler **34** that combines the different pump wavelengths in pump unit **35** may be replaced by a circulator and reflective grating. Specifically, as shown in FIG. **6**, pump sources **50** and **51** generating pump energy at wavelengths λ_1 and λ_2 are respectively coupled to two ports **54** and **55** of a circulator **53**. A reflective grating **57** is disposed between the pump source **51** and port **55** of circulator **53**. The reflective grating **57** is tuned to reflect the wavelength λ_1 generated by pump source **50** and transmit the wavelength λ_2 generated by pump source **51**. In operation, the energy from pump source **50** enters port **54** and is output on port **55**. The reflective grating **57** reflects this energy back to port **55** of circulator **53**. In accordance with the operation of circulator **53**, the combined wavelengths λ_1 and λ_2 directed to port **55** exit the circulator **53** on output port **56** so that the combined pump energy may be directed to coupler **31** shown in FIG. **4**.

What has been described is merely illustrative of the application of the principles of the present invention. Other arrangements and methods can be implemented by those skilled in the art without departing from the spirit and scope of the present invention. For example, the advantages that accrue by combining optical pump sources is not limited to combining two different wavelengths. More generally, a

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plurality of pump wavelengths may be used to further tailor the resulting bandwidth of the Raman amplifier.

The invention claimed is:

1. A Raman amplifier, comprising:

at least a portion of optical fiber in which an optical signal travels;

a pump energy unit that includes first and second pump sources providing pump power at first and second wavelengths, respectively, said first and second wavelengths generating first and second gain profiles in said optical fiber portion;

an optical coupler for coupling said pump power to said optical fiber portion; and

wherein said first and second gain profiles are overlapping.

2. The amplifier of claim **1** wherein said first and second gain profiles are overlapping such that a resulting bandwidth is greater than a bandwidth of each individual gain profile.

3. The amplifier of claim **1** wherein said pump energy unit includes a second optical coupler for combining said first and second wavelengths.

4. The amplifier of claim **1** wherein said pump energy unit further comprises:

a circulator having first and second input ports and an output port, said first and second input ports being respectively coupled to said first and second pump sources; and

a reflective grating disposed between said second input port and said second pump source, said reflective grating being configured to reflect optical energy at the first wavelength and transmit optical energy at the second wavelength.

5. The amplifier of claim **1** wherein said optical signal is a wavelength division multiplexed signal and said optical coupler is a wavelength division multiplexing coupler.

6. The amplifier of claim **1** wherein said first wavelength is approximately equal to 1455 nm and said second wavelength is approximately equal to 1495 nm.

7. The amplifier of claim **1** further comprising a third optical source providing pump power at a third wavelength different from said first and second wavelengths.

8. An optical transmission system, comprising:

first and second transmitter/receiver terminals remotely located with respect to one another;

an optical transmission path coupling said first terminal to said second terminal;

a Raman amplifier providing gain to an optical signal in at least a portion of said optical transmission path, said amplifier including;

a pump energy unit that includes first and second pump sources providing pump power at first and second wavelengths, respectively, said first and second wavelengths generating first and second gain profiles in said optical path portion;

an optical coupler for coupling said pump power to said optical path portion; and

wherein said first and second gain profiles are overlapping.

9. The system of claim **8** wherein said first and second gain profiles are overlapping such that a resulting bandwidth is greater than a bandwidth of each individual gain profile.

10. The system of claim **8** wherein said pump energy unit includes a second optical coupler for combining said first and second wavelengths.

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11. The system of claim **8** wherein said pump energy unit further comprises:

- a circulator having first and second input ports and an output port, said first and second input ports being respectively coupled to said first and second pump sources; and
- a reflective grating disposed between said second input port and said second pump source, said reflective grating being configured to reflect optical energy at the first wavelength and transmit optical energy at the second wavelength.

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12. The system of claim **8** wherein said optical signal is a wavelength division multiplexed signal and said optical coupler is a wavelength division multiplexing coupler.

13. The system of claim **8** wherein said first wavelength is approximately equal to 1455 nm and said second wavelength is approximately equal to 1495 nm.

14. The system of claim **8** further comprising a third optical source providing pump power at a third wavelength different from said first and second wavelengths.

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