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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
13 February 2003 (13.02.2003)

PCT

(10) International Publication Number
WO 03/012488 A2

(51) International Patent Classification⁷: **G02B**

(21) International Application Number: PCT/US02/23943

(22) International Filing Date: 25 July 2002 (25.07.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/916,454 27 July 2001 (27.07.2001) US

(63) Related by continuation (CON) or continuation-in-part (CIP) to earlier application:
US 09/916,454 (CON)
Filed on 27 July 2001 (27.07.2001)

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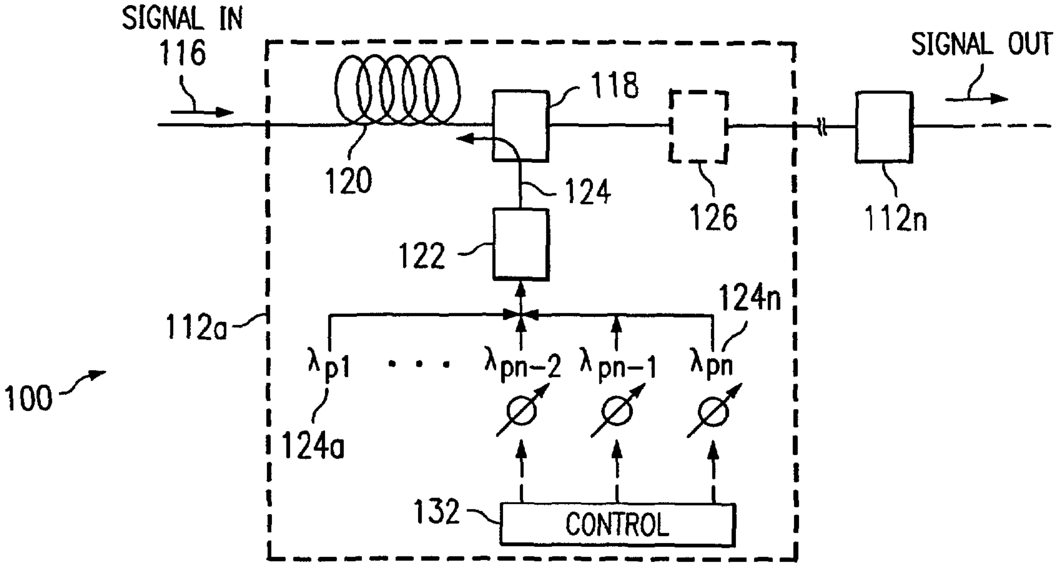
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),

[Continued on next page]

(54) Title: SYSTEM AND METHOD FOR CONTROLLING NOISE FIGURE



(57) Abstract: One aspect of the invention includes an optical amplifier operable to amplify a plurality of optical wavelength signals at least in part through Raman amplification. The amplifier includes an input operable to receive a plurality of wavelength signals and an output operable to communicate an amplified version of at least some of the plurality of wavelength signals. The amplifier further includes a pump assembly operable to generate one or more pump signals and a gain medium operable to receive the plurality of wavelength signals and the one or more pump signals and to facilitate amplification of at least some of the plurality of wavelength signals. The amplifier has associated with it a noise figure having a shape varying as a function of wavelength. At least one of the one or more pump signals is operable to have its power varied to selectively control the shape of the noise figure.

WO 03/012488 A2

European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii)) for the following designations AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZM, ZW, ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG)*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii)) for all designations*

Published:

— *without international search report and to be republished upon receipt of that report*

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SYSTEM AND METHOD FOR CONTROLLING NOISE FIGURE

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to the field of communication systems, and more particularly to a system and method operable to facilitate controlling the shape of a noise figure generated in an optical amplifier.

BACKGROUND

Optical amplifiers generate noise through a variety of phenomena, such as when signals being amplified interact with one another and when signals being amplified interact with pump signals associated with the amplifier. Different levels of noise can be created at different wavelengths along the spectrum of wavelengths being amplified. This leads to a spectrum of noise created across the wavelengths of the amplified signals.

Although optimization techniques can be developed to counter the effects of noise generated by a particular source, the effectiveness of these techniques can deteriorate where the shape of the noise figure changes over time. Existing optimization techniques are generally not equipped to respond to phenomena that tend to change the shape of the noise figure of the amplifier.

OVERVIEW

The present invention recognizes a need for a method and apparatus operable to facilitate control of a noise figure generated in an optical amplifier. In accordance with the present invention, a system and method for controlling a noise figure reduces or eliminates at least some of the shortcomings associated with previous communication systems.

In one aspect of the invention, an optical amplifier operable to amplify a plurality of optical wavelength signals at least in part through Raman amplification comprises an input operable to receive a plurality of wavelength signals and an output operable to communicate an amplified version of at least some of the plurality of wavelength signals. The amplifier further comprises a pump assembly operable to generate one or more pump signals and a gain medium operable to receive the plurality of wavelength signals and the one or more pump signals and to facilitate amplification of at least some of the plurality of wavelength signals. The amplifier has associated with it a noise figure having a shape varying as a function of wavelength. At least one of the one or more pump signals is operable to have its power varied to selectively control the shape of the noise figure.

In another aspect of the invention, a multi-stage amplifier comprises a first amplifier stage comprising a Raman amplification stage operable to amplify a plurality of wavelength signals through interaction with one or more pump signals and a second amplifier stage operable to further amplify at least some of the plurality of wavelength signals. The power of at least one of the one or more pump signals in the first stage is operable to be varied in response to a change in power of the plurality of wavelength signals, the variation in pump power selectively controlling the shape of a noise figure of the amplifier during operation of the amplifier.

In yet another aspect of the invention, an optical amplifier operable to amplify a plurality of optical wavelength signals at least in part through Raman amplification comprises an input operable to receive a plurality of wavelength signals and a pump assembly operable to generate one or more pump signals operable to interact with one or more of the wavelength signals over a gain medium to cause Raman amplification of the one or more wavelength signals. The amplifier also comprises control circuitry operable to generate a control signal based at least in part on a signal proportional to the total power of the plurality of wavelength signals. The amplifier is operable to vary the power of at least one of the one or more pump signals in response to the control signal, the variation of the power of the at least one pump signal selectively controlling the shape of a noise figure associated with wavelength signals being amplified.

In still another aspect of the invention, a method of amplifying a plurality of wavelength signals comprises amplifying a plurality of wavelength signals and adding wavelength signals to or dropping wavelength signals from the plurality of wavelength signals. The method further comprises selectively controlling the shape of the noise figure as wavelength signals are added or dropped from the plurality of wavelength signals.

In another aspect of the invention, a method of amplifying optical signals comprises introducing to a gain medium one or more pump signals and a multiple wavelength signal comprising a plurality of wavelength signals and detecting a change in power of the multiple wavelength signal. The method also comprises adjusting a power of at least one of the one or more pump signals in response to the change in power of the multiple wavelength signal to result in selectively controlling the shape of a noise figure associated with the multiple wavelength signal.

In another aspect of the invention, an optical communication system operable to facilitate communication of multiple signal wavelengths comprises one or more transmitters operable to generate alone or collectively a plurality of signal wavelengths and a multiplexer operable to combine the plurality of signal wavelengths into a single multiple wavelength signal for transmission over a transmission medium. The system further comprises a plurality of optical amplifiers operable to receive the plurality of signal wavelengths. At least one of the optical amplifiers comprises a gain medium operable to amplify the multiple wavelength signal through interaction with one or more pump signals, the amplification occurring prior to, during, or after the multiple wavelength signal's transmission over the transmission medium. The power of at least one of the one or more pump signals is operable to be varied in response to a change in power of the plurality of wavelength signals, the variation in pump power selectively controlling the shape of a noise figure of the amplifier during operation of the amplifier.

Depending on the specific features implemented, particular embodiments of the present invention may exhibit some, none, or all of the following technical advantages. For example, various embodiments of the invention facilitate enhanced amplifier operation by controlling the shape of a noise figure associated with all or a portion of a spectrum of amplified signals.

One aspect recognizes that it would be desirable to maintain the shape of the noise figure in an optical communication system despite changes to the system, such as variations in signal power due to, for example, wavelength signals being added to or dropped from a multiple wavelength signal. This would allow, for example, existing optimization algorithms to continue to be utilized. In addition, in some cases, the peak increase in the noise figure can be lessened by approximately maintaining the shape of the noise figure when system conditions change. Moreover, selectively controlling the shape of the noise figure can reduce or eliminate the need to monitor and adjust individual wavelength signal powers when other wavelength signal powers change.

In at least some embodiments, the shape of a noise figure of an optical amplifier can be effectively modified or maintained by altering the powers of one or more pump wavelengths, in particular pump signals at longer wavelengths. In particular embodiments, all or a majority of the shaping of the noise figure can be accomplished in a first stage of a multiple stage amplifier.

Another aspect recognizes that control signals operable to affect the shape of the noise figure can be generated based at least in part on the total power of the signals being amplified. Although the invention could equally apply to approaches using more complex spectrum analyzing techniques to ascertain a control signal, using total power to determine a control signal provides a simple and cost effective mechanism for controlling noise figure shape. In addition, the relationship between total signal power and adjustments in amplifier pump power to control noise figure shape allows for use of look-up tables or simple algorithms to determine a control signal.

Other technical advantages are readily apparent to one of skill in the art from the attached figures, description, and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, and for further features and advantages thereof, reference is now made to the following description taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is a block diagram showing an exemplary optical communication system operable to facilitate communication of a plurality of wavelength signals according to the teachings of the present invention;

FIGURE 2 is a graphical illustration of a relationship between pump power levels and an optical noise figure for a given signal power;

FIGURES 3a-3c are block diagrams of at least portions of exemplary embodiments of optical amplifiers constructed according to the teachings of the present invention;

FIGURES 4a-4f show exemplary noise figures for various embodiments of optical amplifiers under various operating conditions;

FIGURES 5a-5c are block diagrams illustrating various embodiments of control circuitry operable to generate control signals to modify the power of one or more pump signals according to the teachings of the present invention;

FIGURE 6 is a graph illustrating noise figure shapes resulting from applying a fixed input signal power at various locations along a spectrum of amplified signals according to the teachings of the present invention;

FIGURES 7a-7c are graphs illustrating example pump powers applied in response to various levels of signal power, resulting in approximately maintaining the shape of the optical noise figure for the amplifier as the signal power varies, according to the teachings of the present invention; and

FIGURE 8 is a flowchart illustrating one example of a method of amplifying optical signals.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

FIGURE 1 is a block diagram showing an exemplary optical communication system 10 operable to facilitate communication of a plurality of wavelength signals. System 10 includes a transmitter bank 12 operable to generate a plurality of wavelength signals 16a-16n. Each wavelength signal 16a-16n comprises at least one wavelength or band of wavelengths of light that are substantially different from wavelengths carried by other wavelength signals 16a-16n.

Transmitter bank 12 may include, for example, one or more optical transmitters operable to generate alone or in combination a plurality of wavelength signals 16. In one embodiment, each one of the plurality of transmitters is operable to generate one optical signal having at least one wavelength that is substantially different from wavelengths generated by other transmitters 12. Alternatively, a single transmitter 12 operable to generate a plurality of wavelength signals could be implemented.

System 10 also includes a combiner 14 operable to receive multiple signal wavelengths 16a-16n and to combine those signal wavelengths into a single multiple wavelength signal 16. As one particular example, combiner 14 could comprise a wavelength division multiplexer (WDM). The term wavelength division multiplexer as used herein may include conventional wavelength division multiplexers or dense wavelength division multiplexers.

In one particular embodiment, system 10 may include a booster amplifier 18 operable to receive and amplify wavelengths of signal 16a prior to communication over a transmission medium 20. Transmission medium 20 can comprise multiple spans 20a-20n of fiber. As particular examples, fiber spans 20 could comprise standard single mode fiber (SMF), dispersion-shifted fiber (DSF), non-zero dispersion-shifted fiber (NZDSF), or other fiber type or combinations of fiber types.

Where communication system 10 includes a plurality of fiber spans 20a-20n, system 10 can include one or more in-line amplifiers 22a-22n. In-line amplifiers 22 reside between fiber spans 20 and operate to amplify signal 16 as it traverses fiber 20.

Optical communication system 10 can also include a preamplifier 24 operable to receive signal 16 from a final fiber span 20n and to amplify signal 16 prior to passing that signal to a separator 26. Separator 26 may comprise, for example, a wavelength division demultiplexer (WDM), which can operate on wavelength division multiplexed signals or dense wavelength division multiplexed signals. Separator 26 operates to separate individual wavelength signals 16a-16n from multiple wavelength signal 16. Separator 26 can communicate individual signal wavelength 16a-16n to a bank of receivers 28 and/or other optical communication paths.

Particular optimization techniques can be developed to contend with a specific identified noise sources. The difference (in decibels) between the signal-to-noise ratio (SNR) at the input to the amplifier or amplifier stage and the SNR at an output to the amplifier or amplifier stage is referred to as a noise figure. The shape and magnitude of a noise figure can vary over time and/or according to the source of the noise. For example, the noise figure can change when additional channels are communicated through the system, increasing the aggregate power of the signals being transmitted. Variances in the noise figure can lessen the effectiveness of optimization techniques developed to address a different noise figure spectrum.

One aspect of system 10 recognizes that it would be desirable to maintain the shape of the noise figure in an optical communication system despite changes to the system, such as variations in signal power. This would allow, for example, existing optimization algorithms to continue to be utilized. In addition, in some cases, the peak increase in the noise figure can be lessened by approximately maintaining the shape of the noise figure when system conditions change. Furthermore, maintaining the shape of the noise figure reduces or eliminates the need to monitor and adjust individual wavelength signal powers when other wavelength signal powers change. In this manner, for example, signal-to-noise ratios across the spectrum of amplified wavelengths can be approximately maintained without implementing separate control loops for each signal wavelength.

One way to facilitate this feature is to implement at least one amplification stage in at least one amplifier of system 10 that is operable to perform Raman amplification by introducing to a nonlinear medium signals 16 along with one or more pump signals having various wavelengths. One or more longer wavelength pump signals can be selectively adjusted in power to at least partially control the shape of a noise figure associated with signals 16 being amplified. Throughout this document, the term "longer wavelength pump signal" refers to a pump signal comprising a wavelength that is longer than the wavelengths of at least half of the other pump signals.

In one particular embodiment, the power(s) of one or more longer wavelength pump signals are selectively adjusted in the first amplification stage of a multiple-stage amplifier to result in at least a majority of the shaping of the noise figure being performed in the first amplification stage.

In some cases, the power(s) of one or more longer wavelength pump signals can be adjusted by monitoring the total power of wavelength signals 16 and generating one or more control signals based at least in part on the total power of wavelength signals 16. The control signal(s) can be used to adjust, for example, a current driving the particular one or more pumps, thereby adjusting the power of the pump or pumps.

One aspect of the present invention recognizes that the shape of a noise figure of an optical amplifier can be effectively modified or maintained by altering the powers of one or more pump wavelengths, in particular pump signals at longer wavelengths.

FIGURE 2 is a graphical illustration showing how changing pump powers of various wavelengths affect the shape of a noise figure. FIGURE 2 shows that changes to the power of longer wavelength pump signals have a greater effect, both in magnitude and over a larger bandwidth, than changing the pump power of shorter pump wavelengths.

In FIGURE 2, each noise figure 150a-b, 160a-b, and 170a-b represents an optical noise figure of one particular embodiment of amplifier 100 after varying pump signals at 1450, 1472, and 1505 nanometers, respectively. In this example, the nominal pump powers applied at 1450, 1472, and 1505 nanometers are: 150 milli-Watts, 6.0 milli-Watts, and 1.79 milli-Watts respectively. The graph shows the resulting noise figures when the nominal pump powers are increased and decreased by 1 milli-Watt.

Noise figures 150a, 160a, and 170a show noise figures after pump powers are decreased from their initial powers by 1 milli-Watt. Noise figures 150b, 160b, and 170b show noise figures after the same pumps signals are increased in power by 1 milli-Watt from their initial powers. In each case, the input signal power remains consistent at 75 milli-Watts.

As depicted in FIGURE 2, the shape of noise figures 150a and 150b associated with a pump signal at 1450 nanometers exhibits a relatively small change when the applied pump power changes. In contrast, the shape of noise figures 170a and 170b associated with a longer wavelength pump signal at 1505 nanometers exhibits a much larger change when the applied pump power changes by the same amount.

FIGURE 3a is a block diagram of at least a portion of an exemplary embodiment of an optical amplifier 100. Amplifier 100 comprises at least a first stage 112a comprising a Raman amplification stage. In this example, amplifier 100 further comprises a second stage 112n. Second amplification stage 112n could comprise another Raman amplification stage, or may comprise, for example, a rare-earth doped amplification stage or other amplifier type. Amplifier 100 could comprise a distributed Raman amplifier, a discrete Raman amplifier, or a hybrid amplifier comprising stages of Raman amplification and stages of, for example, rare-earth doped amplification.

System 10 is not limited to a particular number of amplifier stages. For example, amplifier 100 could comprise a single stage amplifier. Alternatively, additional amplification stages could be cascaded after second stage 112n, before stage 112a, or between first stage 112a and second stage 112n.

In this example, first stage 112a of amplifier 100 includes an input operable to receive a multiple wavelength optical input signal 116. First stage 112a also includes a gain medium 120. Depending on the type of amplifier being implemented, medium 120 may comprise, for example, a transmission fiber or a gain fiber such as a spooled gain fiber. In a particular embodiment, medium 120 may comprise a dispersion compensating fiber.

First stage 112a further includes a pump assembly 122. Pump assembly 122 generates a plurality of pump signals 124a-124n (referred to collectively as pump signals 124) at specified wavelengths. Pump assembly 122 may comprise, for example, a single pump operable to generate multiple pump signals 124a-124n at various wavelengths, or may comprise a plurality of pumps, each operable to generate one or more of the pump signals 124a-124n. In a particular embodiment, pump assembly 122 could comprise a polarization multiplexed pump. Although the illustrated embodiment shows the use of counter propagating pumps, co-propagating pumps or a combination of co-propagating and counter-propagating pumps could also be used without departing from the scope of the invention.

The power of one or more pump signals 124 can be selectively altered. In this particular example, one or more control signals 132 operate to facilitate selective adjustment of the power of one or more pump signals 124. In one embodiment, control signal(s) 132 can operate to adjust the current supplied to pump assembly 122, thereby regulating the power produced by one or more pump signals.

As described with respect to FIGURE 2, one aspect of the invention recognizes that adjusting the power of longer wavelength pump signals tends to have a greater effect on the shape of the noise figure than adjusting the power of shorter wavelength pump signals. When seeking to modify or maintain the shape of the noise figure in light of changing signal conditions, therefore, it may be desirable to focus on adjusting the power of longer wavelength pump signals.

Amplifier 100 includes a coupler 118, which couples pump wavelengths 124 to gain medium 120. Coupler 118 could comprise, for example, a wave division multiplexer (WDM) or an optical coupler.

In the illustrated embodiment, one or more lossy elements 126 can optionally reside between first amplifier stage 112a and one or more of subsequent amplification stages 112b-112n. Lossy element 126 could comprise, for example, an isolator, an optical add/drop multiplexer, an optical cross-connect, or a gain equalizer facilitating mid-stage access to the amplifier.

In operation, at first amplification stage 112a, gain medium 120 receives a plurality of wavelength signals and facilitates propagating those signals toward coupler 118. Coupler 118 facilitates communicating pump signals 124 and wavelength signals 116 over gain medium 120. Raman gain results from the interaction of intense light from the pumps with the signals 116 and optical phonons in gain medium 120. The Raman effect leads to a transfer of energy from one optical beam (the pump) to another optical beam (the signal). As conditions change, such as when the power of one or more of wavelength signals 116 changes, or where the aggregate power of the multiple wavelength signal changes, for example, when individual wavelength signals are added or dropped, control signal(s) 132 is applied to pump assembly 122 to approximately maintain the shape of the noise figure associated with the signals being amplified.

FIGURE 3b is a block diagram showing one particular example of a multiple stage amplifier 105 operable to control noise figure shape and gain shape. Amplifier 105 includes a first stage 107 and a second stage 109. First stage 107 includes a Raman gain medium 121 operable to receive a multiple wavelength signal 116 and one or more pump signals 124. The power of one or more of pump signals

124 is varied to adjust the shape of the noise figure associated with amplification stage 107.

Second stage 109 includes an amplification medium 123 operable to receive multiple wavelength signal 116 and one or more pump signals. Gain medium 123 may comprise a Raman gain medium or a rare-earth doped gain medium. Gain medium 123 also receives pump signals 125. One or more pump signals 125 are adjusted to adjust or flatten the gain of amplifier stage 109, and/or the entire amplifier assembly 105. A gain flattening filter could alternatively be used to flatten the gain of amplifier stage 109 and/or amplifier assembly 105.

FIGURE 3c is a block diagram showing another embodiment of a multiple stage amplifier 111 operable to adjust the shape of a noise figure. Amplifier 111 comprises a first stage 117 comprising a distributed Raman amplification stage and a second stage 119 comprising a discrete Raman amplification stage. The powers of one or more pump signals 123 and/or 125 can be adjusted to modify the shape of a noise figure associated with amplification stages 117 and/or 119, or amplifier assembly 111. A lossy element 121, such as an optical isolator can be coupled between stages of amplifier 111. Lossy element 121 can facilitate, for example, mid-stage access to amplifier 111.

FIGURE 4a shows exemplary noise figures for amplifier 100 applying various levels of input signal power while the powers of pump signals 124 remain approximately constant. In this example, wavelength signals range in wavelength from 1520 nanometers to 1610 nanometers. Noise figures 200a-200d represent noise figures for total input signal powers of 0.0

milli-Watts, 50 milli-Watts; 100 milli-Watts; and 200 milli-Watts; respectively.

In this example, amplifier 100 comprises a two stage Raman amplifier. First stage 112a utilizes approximately eighty kilometers of SMF-28 fiber as a gain medium and six pump signals 124. Second stage 112n utilizes a length of dispersion compensating fiber, such as DK-30 available from Lucent Technologies, and two pump signals. The powers and spectral locations of the pump signals in the first stage, for all input signal power levels, are as follows:

438 milli-Watts at 1396 nanometers;
438 milli-Watts at 1416 nanometers;
438 milli-Watts at 1427 nanometers;
254 milli-Watts at 1450 nanometers;
15 milli-Watts at 1472 nanometers;
10 milli-Watts at 1505 nanometers.

These values, including the location, number, and powers for each pump signal, are given for illustrative purposes only and are not intended to limit the scope of the invention. As depicted in FIGURE 4a, as the signal power increases from a nominal value (noise figure 200a) to a value of 200 milli-Watts (noise figure 200d), the shape of the noise figure changes, resulting in a generally steeper sloped noise figure as the signal power increases. As a result, optimization schemes developed for use with noise figure 200a can become less effective, or even unusable as the signal power level increases. In addition, the peak noise level increases as signal power increases.

FIGURE 4b shows exemplary noise figures for the same amplifier 100 when applying various levels of input signal power. In this case, however, the longest wavelength pump signal is modified to result in approximately maintaining the shape of the noise figure. In this example, the longest wavelength pump signal (1505 nanometers) power level was modified as the input signal power changed as follows:

10 milli-Watts for signal power = 0 milli-Watts;
8 milli-Watts for signal power = 50 milli-Watts;
6 milli-Watts for signal power = 100 milli-Watts;
2 milli-Watts for signal power = 200 milli-Watts.

Again, the spectral location and power of the pump signal being modified are given for illustrative purposes only. In this example, as depicted in FIGURE 4b, modifying the power of a longer wavelength pump signal, in this case the longest wavelength pump signal, as the power of input signals 116 increases can result in approximately maintaining the shape of the noise figure for the amplifier or for a particular amplifier stage. As a result, optimization techniques developed for one noise figure can continue to be applied despite changes in system characteristics, such as input signal power, that would otherwise significantly change the shape of the noise figure. In addition, FIGURE 4b shows that adjusting the power of one or more of the longer wavelength pump signals can result in reducing the increase in the peak noise figure compared to approaches leaving all pump powers constant. Moreover, using this technique, the relative signal-to-noise ratio for each individual wavelength signal can be approximately maintained without requiring a feedback loop for each wavelength.

As an additional feature, the embodiment depicted in FIGURE 3 implements a gain flattening technique to achieve a more uniform gain spectrum. In particular, the pump signals in second amplification stage 112n have been selected to increase the flatness of the gain curve. In this example, pump signals of 380 milli-Watts are applied at 1472 nanometers and 1505 nanometers, respectively, in second stage 112n. This embodiment illustrates selection of pump power levels in an early amplification stage to address modifications of the shape of the noise figure, and modification of the power of those pump signals in a later stage of the amplifier to address flattening of the amplifier gain spectrum. Of course, other gain flattening techniques, such as use of a gain flattening filter could alternatively be used to achieve similar results.

FIGURES 4c and 4d are graphs illustrating noise figures for uncompensated and compensated operation, respectively, of another embodiment of amplifier 100. In this example, wavelength signals range in wavelength from 1520 nanometers to 1610 nanometers. Noise figures 210a-210d represent noise figures for total input signal powers of 0.0 milli-Watts, 50 milli-Watts; 100 milli-Watts; and 200 milli-Watts; respectively.

In this embodiment, amplifier 100 comprises a two stage Raman amplifier. The gain medium in the first amplification stage comprises approximately 80 kilometers of LEAF Raman gain fiber. The second stage comprises a dispersion compensating fiber, such as DK-30 fiber available from Lucent Technologies.

The powers and spectral locations of the pump signals in the first stage of this example, for all input signal power levels, are as follows:

438 milli-Watts at 1396 nanometers;
438 milli-Watts at 1416 nanometers;
438 milli-Watts at 1427 nanometers;
200 milli-Watts at 1450 nanometers;

8 milli-Watts at 1472 nanometers;
4.5 milli-Watts at 1505 nanometers.

Again, these values, including the location, number and powers for each pump signal, are given for illustrative purposes only and are not intended to limit the scope of the invention. As depicted in FIGURE 4c, as the signal power increases from a nominal value (noise figure 210a) to a value of 200 milli-Watts (noise figure 210d), the shape of the noise figure changes, resulting in a generally steeper sloped noise figure as the signal power increases. In addition, the peak noise level increases as signal power increases.

FIGURE 4d shows exemplary noise figures for the same amplifier 100 when applying various levels of input signal power, while modifying a longer wavelength pump signal to result in approximately maintaining the shape of the noise figure. In this example, the longest wavelength pump signal (1505 nanometers) power level was modified as the input signal power changed as follows:

4.5 milli-Watts for signal power = 0 milli-Watts;
3.8 milli-Watts for signal power = 50 milli-Watts;
2.9 milli-Watts for signal power = 100 milli-Watts;
0.5 milli-Watts for signal power = 200 milli-Watts.

Again, the spectral location and power of the pump signal being modified are given for illustrative purposes only. In this example, as depicted in FIGURE 4d, decreasing the power of the longest wavelength pump signal 324 as the power of input signals 116 increases results in approximately maintaining the shape of the noise figure for the amplifier or for a particular amplifier stage.

The concept of utilizing adjustments to longer wavelength pump signals to approximately maintain the shape of the noise figure is not limited to making adjustments to just one pump wavelength. FIGURES 4e and 4f are graphs illustrating noise figures for uncompensated and compensated operation, respectively, of still another embodiment of amplifier 100. In this example, wavelength signals ranged in wavelength from 1520 nanometers to 1610 nanometers. Noise figures 220a-220d represent noise figures for total input signal powers of 0.0 milli-Watts, 50 milli-Watts; 100 milli-Watts; and 150 milli-Watts; respectively.

In this embodiment, amplifier 100 comprises a two stage Raman amplifier, where the first stage implements an approximately 80 kilometer length of TrueWave Raman fiber. The second stage uses a dispersion compensating fiber, such as a DK-30 fiber available from Lucent Technologies. The powers and spectral locations of the pump signals in the first stage of this example, for all input signal power levels, are as follows:

320	milli-Watts at 1396 nanometers;
320	milli-Watts at 1416 nanometers;
320	milli-Watts at 1427 nanometers;
150	milli-Watts at 1450 nanometers;
4.7	milli-Watts at 1472 nanometers;
2.9	milli-Watts at 1505 nanometers.

As depicted in FIGURE 4e, as the signal power increases from a nominal value (noise figure 220a) to a value of 150 milli-Watts (noise figure 220d), the shape of the noise figure changes, resulting in a generally steeper sloped noise figure as the signal power increases. In addition, the peak noise level increases as signal power increases.

FIGURE 4f shows exemplary noise figures for the same amplifier 100 when applying various levels of input signal power, while adjusting the longest two wavelength pump signals. In this example, the power of the longest wavelength pump signal (1505 nanometers) was modified as the input signal power changed as follows:

2.9 milli-Watts for signal power = 0 milli-Watts;
2.3 milli-Watts for signal power = 50 milli-Watts;
1.2 milli-Watts for signal power = 100 milli-Watts;
0.1 milli-Watts for signal power = 150 milli-Watts.

In addition, the power level of the second-longest wavelength pump signal (in this case 1472 nanometers) was modified as the input signal power changed as follows:

4.7 milli-Watts for signal power = 0 milli-Watts;
6.0 milli-Watts for signal power = 50 milli-Watts;
6.0 milli-Watts for signal power = 100 milli-Watts;
6.0 milli-Watts for signal power = 150 milli-Watts.

Again, the spectral location and power of the pump signal being modified are given for illustrative purposes only. As depicted in FIGURE 4f, decreasing the power of multiple longer wavelength pump signals 324 as the power of input signals 116 increases can result in approximately maintaining the shape of the noise figure for the amplifier or for a particular amplifier stage.

FIGURES 5a-5c are block diagrams illustrating various embodiments of control circuitry 330 operable to generate control signals 332 to modify the power of one or more pump signals 324. Each of FIGURES 5a-5c shows one stage of an optical amplifier including a gain medium 320 operable to receive a multiple wavelength signal 316. Gain medium 320 is coupled to a coupler 318, which facilitates introduction of pump signal 324 to gain medium 320. Wavelength signal

316 is amplified as one or more pump signals 324 interact with one or more wavelength signals of multiple wavelength 316 along gain medium 320. An amplified version 326 of wavelength signal 316 is output from the amplifier stage.

Each of the amplifiers in FIGURE 5a-5c includes control circuitry 330 operable to generate a control signal 332. Control signal 332 may, for example, adjust the current supplied to pump assemblies 322 for generating one or more pump signals 324. Control circuitry 330 may generate control signal 332 based on, for example, a signal proportional to the total input signal power of wavelength signal 316 as shown in FIGURE 5a, based on a signal proportional to the total signal power of output signal 326 as shown in FIGURE 5b, or based on a comparison of signals proportional to the total signal power of input wavelength signal 316 and output signal 326 as shown in FIGURE 5c. Throughout this document, discussions of determining a control signal based on a total power of the optical signal are intended to encompass situations where a signal proportional to the total power of the optical signal is used to generate the control signal.

FIGURE 6 is a graph illustrating noise figure shapes resulting from applying a fixed input signal power at various locations along a spectrum ranging from 1,520-1,620 nanometers. As shown in FIGURE 6, although the magnitude of the noise figure may vary depending on the spectral location of the input signal power, in this embodiment the shape of the noise figure generally remains constant regardless of the spectral location of the signal power. One aspect of this invention recognizes that at least for embodiments similar to this one, when the shape of the noise figure does not significantly change depending on the spectral location of the input signal power, a control signal 322 can be generated by measuring the total signal power (for example, by using a signal proportional to the total signal power).

While more complex techniques such as implementing a spectrum analyzer to determine noise levels at particular wavelength ranges could be used without departing from the scope of the invention, using the total signal power to determine a control signal 332 provides advantages by reducing the cost and complexity of the system. Thus, signals 340 and 350 provide information regarding the total power of input signal 316, and signals 345 and 355 provide information regarding the total signal power of output signal 326.

FIGURES 7a-7c are graphs illustrating example pump powers applied in response to various levels of signal power, resulting in approximately maintaining the shape of the optical noise figure for the amplifier as the signal power varies. FIGURE 7a corresponds to the example discussed in FIGURE 4b. FIGURE 7b corresponds to the example discussed in FIGURE 4d. FIGURE 7c corresponds to the example discussed in FIGURE 4f.

In these examples, ten signal wavelengths are applied over a range of 1,520-1,610 nanometers in Raman amplifier stages using various gain media. For example, FIGURE 7a shows the results of a Raman amplifier stage using an SMF-28 distribution fiber as a gain medium. This figure illustrates changes in power to a pump signal at 1,505 nanometers that will achieve an approximately consistent shape of noise figure as signal powers vary from zero to 200 milli-watts.

The graph in FIGURE 7b shows pump powers to be applied at 1,505 nanometers to achieve an approximately consistent noise figure shape for a Raman amplifier using a LEAF distribution fiber as a gain medium. FIGURE 7c shows pump powers to be applied at 1,505 nanometers and 1,472 nanometers to achieve approximately consistent noise figure shapes for signal powers ranging from zero milli-watts to 150 milli-watts in a Raman amplifier using a TrueWave distribution fiber as a gain medium.

As shown in FIGURES 7a-7c, one aspect of the present invention recognizes that adjustments to pump power for given changes in signal power can be nearly linear in nature. As a result, control circuitry 330 could comprise, for example, a look-up table or logic implementing an equation describing the relationship between changes in pump power and changes in signal power. Throughout this document, the term "logic" refers to any hardware, software, firmware, or combination thereof operable to execute one or more instructions, functions, processes, or routines to return on or more results.

For example, where control circuitry 330 comprises a look-up table, the table could be indexed according to signal powers 340 and/or 345 measured from input and output signals 316 and 326, respectively. For given signal powers, the look-up table of control circuitry 330 could index a value for control signal 332 resulting in a desired pump power. Likewise, where control circuitry 330 comprises logic implementing an equation describing the relationship between pump power and signal power, for given signal power applied to control circuitry 330, control circuitry 330 could generate control signal 332 directing pump 322 to produce pump signal 334 at a desired power level.

FIGURE 8 is a flowchart illustrating one example of a method 400 of amplifying optical signals. This particular example will be discussed with respect to the embodiment described in FIGURE 3 comprising a two-stage optical amplifier including at least a first stage operable to provide Raman amplification.

Method 400 begins at step 410 where amplifier 100 introduces a multiple wavelength signal 116 to gain medium 120. Multiple wavelength signal carries a plurality of individual wavelength signals. Gain medium 120, in this particular example, comprises a distributed Raman gain medium.

Amplifier 100 introduces one or more pump signals 324 to gain medium 120 at step 420. In this particular example, pump assembly 122 generates a plurality of pump signals 124a-124n, each having a wavelength distinct from wavelengths of other pump signals 124. Pump assembly 122 communicates pump signals 124 to a coupler 118, which facilitates propagation of pump signals 124 along gain medium 120 along with multiple wavelength signal 116. Pump signals 124 can co-propagate in the same direction as multiple wavelength signal 116, may counter-propagate in an opposite direction from multiple wavelength signal 116 over gain medium 120, or may include a combination of co-propagating and counter-propagating pump signals.

At least some wavelength signals of multiple wavelength signal 116 interact with at least some pump signals 124 at step 430 as those signals traverse gain medium 120. In this example, Raman gain results from interaction between pump signals 128, multiple wavelength signal 116, and optical phonons in silica fibers of gain medium 120. The Raman effect leads to a transfer of energy from pump signals 124 to wavelength signals of multiple wavelength signal 116.

Controller 132 monitors a characteristic, such as the power of multiple wavelength signal 116 at step 440. In a particular embodiment, controller 132 monitors the total signal power of wavelength signal 116. Control 132 may monitor the total signal power of signal 116 at various locations such as, the input to amplifier 100, or at a mid-stage point of amplifier 100. The total signal power can be approximated, for example, by tapping a portion of signal 116 to obtain a signal proportional to the total signal power.

In the event that a change in signal power is detected at step 140, controller 132 generates a control signal operable to adjust the power of at least one pump signal at step 450 to adjust the shape of a noise figure associated with multiple wavelength signal 116. A change in signal power could arise, for example, when powers of individual wavelength signals are varied, or when individual wavelength signals are added to or dropped from multiple wavelength signal 116.

In a particular embodiment, controller 132 adjusts the power of one or more longer wavelength pump signals 124. In one particular embodiment, controller 132 may adjust only the longest wavelength pump signal 124 to approximately maintain the shape of the noise figure under changing conditions of the multiple wavelength signal. All or most of the adjustment of the shape of the noise figure can occur, for example, in the first stage of a multiple stage amplifier.

Although the present invention has been described in several embodiments, a myriad of changes, variations, alterations, transformations, and modifications may be suggested to one skilled in the art, and it is intended that the present invention encompass such changes, variations, alterations, transformations, and modifications as fall within the spirit and scope of the appended claims.

WHAT IS CLAIMED IS:

1. An optical amplifier operable to amplify a plurality of optical wavelength signals at least in part through Raman amplification, the amplifier comprising:

an input operable to receive a plurality of wavelength signals;

an output operable to communicate an amplified version of at least some of the plurality of wavelength signals;

a pump assembly operable to generate one or more pump signals; and

a gain medium operable to receive the plurality of wavelength signals and the one or more pump signals and to facilitate amplification of at least some of the plurality of wavelength signals;

wherein the amplifier has associated with it a noise figure having a shape varying as a function of wavelength and wherein at least one of the one or more pump signals is operable to have its power varied to selectively control the shape of the noise figure.

2. The amplifier of Claim 1, wherein the at least one of the one or more pump signals is operable to have its power varied to contribute to approximately maintaining the shape of the noise figure as the power of at least one of the plurality of optical wavelength signals varies or wavelength signals are added to or dropped from the plurality of wavelength signals.

3. The amplifier of Claim 1, wherein the at least one of the one of more pump signals comprises a pump signal having a longer wavelength than wavelengths of at least half of the one or more pump signals.

4. The amplifier of Claim 1, wherein the at least one of the one of more pump signals comprises a pump signal having a longer wavelength than wavelengths of any of the other one or more pump signals.

5. The amplifier of Claim 1, wherein the at least one of the one or more pump signals comprises a plurality of pump signals each having a longer wavelength than wavelengths of at least half of the one or more pump signals.

6. The amplifier of Claim 1, wherein the pump assembly comprises a plurality of pumps each operable to generate one of a plurality of pump signals.

7. The amplifier of Claim 1, wherein the gain medium comprises a transmission fiber.

8. The amplifier of Claim 1, wherein the gain medium comprises a Raman gain fiber.

9. The amplifier of Claim 1, wherein the amplifier comprises a multiple stage amplifier, and wherein the input, the gain medium, and the pump assembly reside in a first amplifier stage of the multiple stage amplifier.

10. The amplifier of Claim 9, wherein a majority of control of the shape of the noise figure occurs in the first amplifier stage.

11. The amplifier of Claim 9, wherein a pump power in the first amplifier stage is varied to control the shape of the noise figure, and wherein a pump power in a second amplifier stage is varied to control the flatness of the gain of the wavelength signals.

12. The amplifier of Claim 9, wherein a pump power in the first amplifier stage is varied to control the shape of the noise figure, and when a gain flattening filter is applied to control the flatness of the gain of the wavelength signals.

13. The amplifier of Claim 1, wherein the amplifier comprises at least one distributed Raman amplification stage.

14. The amplifier of Claim 1, wherein the amplifier comprises at least one discrete Raman amplification stage.

15. The amplifier of Claim 1, wherein the amplifier comprises a multiple stage amplifier comprising:

at least one stage comprising a distributed Raman amplifier; and

at least one stage comprising a discrete Raman amplifier.

16. The amplifier of Claim 1, wherein the amplifier comprises a multiple stage amplifier comprising:

at least one stage of Raman amplification; and

at least one stage of rare-earth doped amplification.

17. The amplifier of Claim 1, wherein the amplifier comprises a multiple stage amplifier, comprising a lossy element coupled between two amplification stages.

18. The amplifier of Claim 17, wherein the lossy element is selected from a group consisting of an optical add/drop multiplexer, an optical cross-connect, a gain equalizer, and an optical isolator.

19. The amplifier of Claim 17, wherein the lossy element is operable to provide mid-stage access to the amplifier.

20. An optical amplifier comprising,

an input operable to receive a plurality of wavelength signals;

an output operable to communicate an amplified version of at least some of the plurality of wavelength signals;

wherein the amplifier has associated with it a noise figure having a shape varying as a function of wavelength; and

means for selectively controlling the shape of the noise figure as wavelength signals are added to or dropped from the plurality of wavelength signals.

21. The amplifier of Claim 20, wherein the means for selectively controlling the shape of the noise figure comprises a controller operable to generate a control signal operable to cause a change in a pump power of the amplifier.

22. The amplifier of Claim 21, wherein the pump power drives a first amplification stage of a multiple stage amplifier.

23. The amplifier of Claim 22, wherein the multiple stage amplifier comprises a discrete Raman amplification stage and a distributed Raman amplification stage.

24. The amplifier of Claim 21, wherein the control signal is generated based at least in part on a total power of the plurality of wavelength signals.

25. The amplifier of Claim 20, wherein the amplifier comprises at least one Raman amplification stage.

26. A multi-stage amplifier, comprising:

a first amplifier stage comprising a Raman amplification stage operable to amplify a plurality of wavelength signals through interaction with one or more pump signals;

a second amplifier stage operable to further amplify at least some of the plurality of wavelength signals;

wherein the power of at least one of the one or more pump signals in the first stage is operable to be varied in response to a change in power of the plurality of wavelength signals, the variation in pump power selectively controlling the shape of a noise figure of the amplifier during operation of the amplifier.

27. The amplifier of Claim 26, wherein the variation in pump power in the first stage is operable to approximately maintain the shape of a noise figure associated with the first stage as the power of one or more of the plurality of wavelength signals changes or wavelength signals are added to or dropped from the plurality of wavelength signals.

28. The amplifier of Claim 26, wherein a majority of the control of the shape of the noise figure occurs in the first Raman amplifier stage.

29. The amplifier of Claim 26, wherein substantially all of the control of the shape of the noise figure occurs in the first Raman amplifier stage.

30. The amplifier of Claim 26, wherein the at least one of the one or more pump signals in the first stage comprises a pump signal having a longer wavelength than wavelengths of at least half of the one or more pump signals.

31. The amplifier of Claim 26, wherein the at least one of the one or more pump signals comprises a pump signal having a longer wavelength than wavelengths of any of the other one or more pump signals.

32. The amplifier of Claim 26, wherein the at least one of the one or more pump signals comprises a plurality of pump signals each having a longer wavelength than wavelengths of at least half of the one or more pump signals.

33. The amplifier of Claim 26, wherein a pump power in the first stage is varied to control the shape of the noise figure, and wherein a pump power in the second stage is varied to control the flatness of the gain of the wavelength signals.

34. The amplifier of Claim 26, wherein the second amplifier stage comprises a rare-earth doped amplifier stage.

35. The amplifier of Claim 26, further comprising at least one additional amplification stage coupled between the first and second amplification stages.

36. The amplifier of Claim 26, wherein the amplifier comprises a distributed Raman amplifier.

37. The amplifier of Claim 26, wherein the amplifier comprises a discrete Raman amplifier.

38. The amplifier of Claim 26, wherein the first stage of the amplifier comprises a distributed Raman amplifier, and wherein the second stage of the amplifier comprises a discrete Raman amplifier.

39. The amplifier of Claim 26, wherein the amplifier comprises a lossy element coupled between the first and second amplification stages.

40. The amplifier of Claim 39, wherein the lossy element is selected from a group consisting of an optical add/drop multiplexer, an optical cross-connect, a gain equalizer, and an optical isolator.

41. The amplifier of Claim 26, wherein the lossy element is operable to provide mid-stage access to the amplifier.

42. An optical amplifier operable to amplify a plurality of optical wavelength signals at least in part through Raman amplification, the amplifier comprising:

an input operable to receive a plurality of wavelength signals;

a pump assembly operable to generate one or more pump signals operable to interact with one or more of the wavelength signals over a gain medium to cause Raman amplification of the one or more wavelength signals; and

control circuitry operable to generate a control signal based at least in part on a signal proportional to the total power of the plurality of wavelength signals;

wherein the amplifier is operable to vary the power of at least one of the one or more pump signals in response to the control signal, the variation of the power of the at least one pump signal selectively controlling the shape of a noise figure associated with wavelength signals being amplified.

43. The amplifier of Claim 42, wherein the control circuitry comprises a look-up table.

44. The amplifier of Claim 43, wherein the look-up table comprises values operable to be adjusted over time to account for changes in amplifier characteristics over time.

45. The amplifier of Claim 42, wherein the total power of the wavelength signals comprises the total power of the wavelength signals at an input to the amplifier.

46. The amplifier of Claim 42, wherein the total power of the wavelength signals comprises the total power of the wavelength signals at an output of the amplifier.

47. The amplifier of Claim 42, wherein the control circuitry comprises logic operable to determine the control signal by applying an equation describing a relationship between the total power of the wavelength signals and pump power.

48. The amplifier of Claim 42, wherein the control circuitry comprises a comparison circuit operable to determine a difference between the total power of the wavelength signals at an input to the amplifier and the total power of the wavelength signals at an output to the amplifier.

49. The amplifier of Claim 42, wherein at least one of the one or more pump signals comprises a pump signal having a longer wavelength than wavelengths of at least half of the one or more pump signals.

50. The amplifier of Claim 42, wherein the at least one of the one or more pump signals comprises a pump signal having a longer wavelength than wavelengths of any of the other one or more pump signals.

51. The amplifier of Claim 42, wherein the at least one of the one or more pump signals comprises a plurality of pump signals each having a longer wavelength than wavelengths of at least half of the one or more pump signals.

52. The amplifier of Claim 42, further comprising an optical tap operable to direct a portion of each of the plurality of wavelength signals to the control circuitry, the portion comprising an optical signal having a total power that is proportional to the total power of the plurality of wavelength signals.

53. A method of amplifying a plurality of wavelength signals, comprising:

amplifying a plurality of wavelength signals;

adding wavelength signals to or dropping wavelength signals from the plurality of wavelength signals; and

selectively controlling the shape of the noise figure as wavelength signals are added or dropped from the plurality of wavelength signals.

54. The method of Claim 53, wherein amplifying the plurality of wavelength signals comprises amplifying the plurality of signals in a discrete Raman amplification stage.

55. The method of Claim 53, wherein amplifying the plurality of wavelength signals comprises amplifying the plurality of signals in a distributed Raman amplification stage.

56. The method of Claim 53, wherein selectively controlling the shape of the noise figure comprises approximately maintaining the shape of the noise figure.

57. The method of Claim 53, wherein selectively controlling the shape of the noise figure comprises selectively adjusting a power of one or more pump signals driving at least one amplifier stage.

58. The method of Claim 57, wherein the one or more pump signals each comprise a wavelength that is longer than wavelengths of at least half of the one or more pump signals.

59. The method of Claim 57, wherein the one or more pump signals each comprise a wavelength that is longer than any of the other one or more pump signals.

60. The method of Claim 57, wherein adjusting a power of one or more pump signals comprises adjusting the power of one or more pump signals based at least in part on a total power of the plurality of wavelength signals.

61. The method of Claim 57, wherein the at least one amplifier stage comprises a first amplifier stage of a multiple stage amplifier.

62. A method of amplifying optical signals, comprising:

introducing to a gain medium one or more pump signals and a multiple wavelength signal comprising a plurality of wavelength signals;

detecting a change in power of the multiple wavelength signal;

selectively adjusting a power of at least one of the one or more pump signals in response to the change in power of the multiple wavelength signal to result in selectively controlling the shape of a noise figure associated with the multiple wavelength signal.

63. The method of Claim 62, wherein the at least one of the one of more pump signals comprises a pump signal having a longer wavelength than wavelengths of at least half of the one or more pump signals.

64. The method of Claim 62, wherein the at least one of the one of more pump signals comprises a pump signal having a longer wavelength than wavelengths of any of the other one or more pump signals.

65. The method of Claim 62, wherein the at least one of the one or more pump signals comprises a plurality of pump signals each having a longer wavelength than wavelengths of at least half of the one or more pump signals.

66. The method of Claim 62, wherein detecting a change in power of the multiple wavelength signal comprises detecting a change in a total power of the multiple wavelength signal.

67. The method of Claim 66, wherein detecting a change in the total power of the multiple wavelength signal comprises receiving a signal proportional to the total power of the multiple wavelength signal.

68. The method of Claim 66, wherein detecting a change in the total power of the multiple wavelength signal comprises detecting a change of the total power of the multiple wavelength signal at or prior to an input to the gain medium.

69. The method of Claim 66, wherein detecting a change in the total power of the multiple wavelength signal comprises detecting a change of the total power of the multiple wavelength signal at or after an output from the gain medium.

70. The method of Claim 62, wherein detecting a change in power of the multiple wavelength signal comprises detecting a change in the number of wavelength signals in the plurality of wavelength signals.

71. The method of Claim 62, wherein selectively adjusting a power of at least one of the one or more pump signals comprises adjusting the power of the at least one of the one or more pump signals in a first amplification stage of a multiple stage amplifier.

72. The method of Claim 71, further comprising applying a gain flattening technique in a subsequent amplification stage to the first amplification stage.

73. The method of Claim 72, wherein the gain flattening technique comprises adjusting a pump power in the subsequent amplification stage.

74. The method of Claim 62, wherein selectively adjusting a power of at least one of the one or more pump signals results in maintaining an approximately consistent shape of the noise figure before and after the change in power of the multiple wavelength signal.

75. The method of Claim 62, wherein the gain medium comprises a transmission fiber in a distributed Raman amplification stage.

76. The method of Claim 62, wherein the gain medium comprises a Raman gain fiber in a discrete Raman amplification stage.

77. An optical communication system operable to facilitate communication of multiple signal wavelengths, the system comprising:

one or more transmitters operable to generate alone or collectively a plurality of signal wavelengths;

a multiplexer operable to combine the plurality of signal wavelengths into a single multiple wavelength signal for transmission over a transmission medium; and

a plurality of optical amplifiers operable to receive the plurality of signal wavelengths, at least one of the optical amplifiers comprising:

a gain medium operable to amplify the multiple wavelength signal through interaction with one or more pump signals, the amplification occurring prior to, during, or after the multiple wavelength signal's transmission over the transmission medium;

wherein the power of at least one of the one or more pump signals is operable to be selectively varied in response to a change in power of the plurality of wavelength signals, the variation in pump power selectively controlling the shape of a noise figure of the amplifier during operation of the amplifier.

78. The system of Claim 77, wherein the at least one of the one or more pump signals comprises a longer wavelength pump signal.

79. The system of Claim 78, wherein the longer wavelength pump signal comprises a pump signal comprising a longer wavelength than any of the other of the at least one pump signals.

80. The system of Claim 77, wherein the at least one amplifier comprises control circuitry operable to generate a control signal based at least in part on a signal proportional to the total power of the multiple wavelength signal, wherein the amplifier is operable to vary the power of the at least one of the one or more pump signals in response to the control signal.

81. The system of Claim 77, wherein the at least one of the one or more pump signals is operable to have its power selectively varied to contribute to approximately maintaining the shape of the noise figure as the total power of the plurality of optical wavelength signals varies or as wavelength signals are added to or dropped from the plurality of wavelength signals.

82. The system of Claim 77, wherein the at least one amplifier comprises a multiple stage amplifier.

83. The system of Claim 82, wherein a majority of control of the shape of the noise figure occurs in a first amplifier stage of the multiple stage amplifier.

84. The system of Claim 83, wherein a pump power in the first amplifier stage is varied to control the shape of the noise figure, and wherein a pump power in a second amplifier stage is varied to control the flatness of the gain of the wavelength signals.

85. The system of Claim 83, wherein a pump power in the first amplifier stage is varied to control the shape of the noise figure, and when a gain flattening filter is applied to control the flatness of the gain of the wavelength signals.

86. The system of Claim 77, wherein the at least one amplifier comprises a distributed Raman amplifier.

87. The system of Claim 77, wherein the at least one amplifier comprises a discrete Raman amplifier.

88. The system of Claim 77, wherein the at least one amplifier comprises a multiple stage amplifier comprising:

at least one stage comprising a distributed Raman amplifier; and

at least one stage comprising a discrete Raman amplifier.

89. The system of Claim 77, wherein the at least one amplifier comprises a multiple stage amplifier comprising:

at least one stage of Raman amplification; and

at least one stage of rare-earth doped amplification.

90. The system of Claim 77, wherein the at least one amplifier comprises a multiple stage amplifier, comprising a lossy element coupled between two amplification stages the lossy element.

91. The system of Claim 90, wherein the lossy element is selected from a group consisting of an optical add/drop multiplexer, an optical cross-connect, a gain equalizer, and an optical isolator.

92. The system of Claim 90, wherein the lossy element is operable to provide mid-stage access to the at least one amplifier.

93. The system of Claim 77, further comprising:

a demultiplexer operable to receive the multiple wavelength signal and to separate the signal wavelengths from the multiple wavelength signal; and

a receiver bank operable to receive the plurality of signal wavelengths.

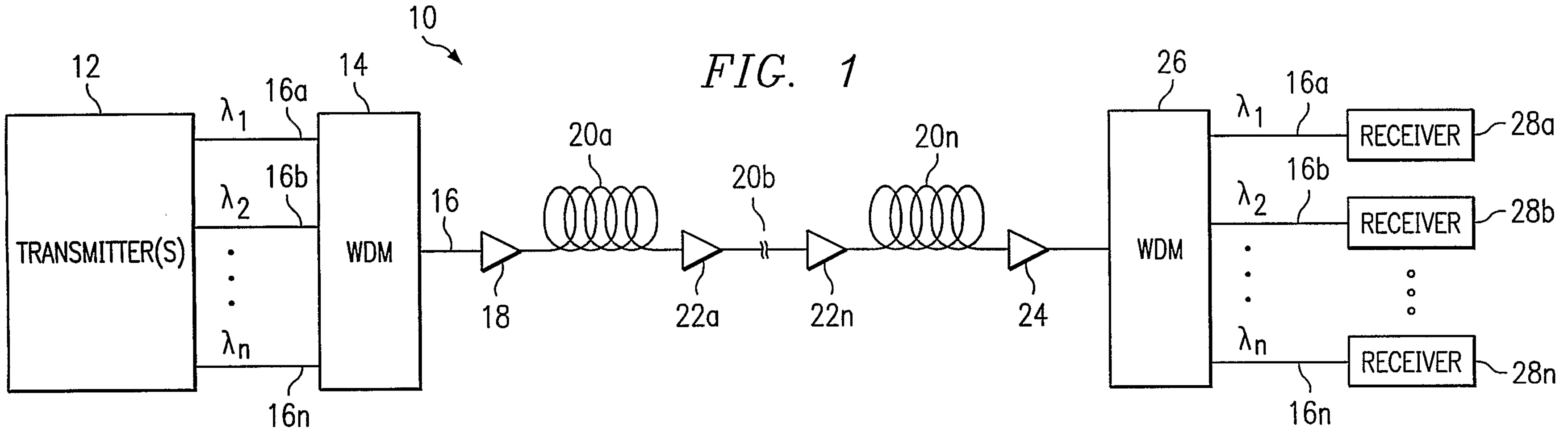
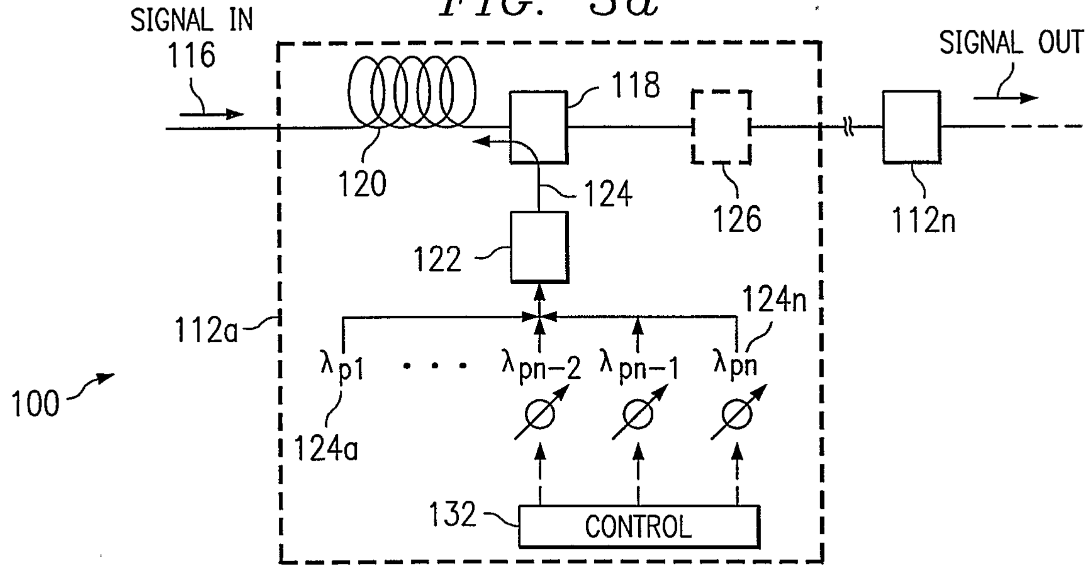

10
12
TRANSMITTER(S)
λ_1
λ_2
λ_n
16a
16b
16n
14
WDM
16
18
20a
22a
20b
22n
20n
24
26
WDM
λ_1
λ_2
λ_n
16a
16b
16n
RECEIVER
RECEIVER
RECEIVER
28a
28b
28n

FIG. 1

FIG. 3a


SIGNAL IN
116
120
118
124
126
112n
SIGNAL OUT
122
112a
100
λ_{p1}
λ_{pn-2}
λ_{pn-1}
λ_{pn}
124a
124n
132
CONTROL

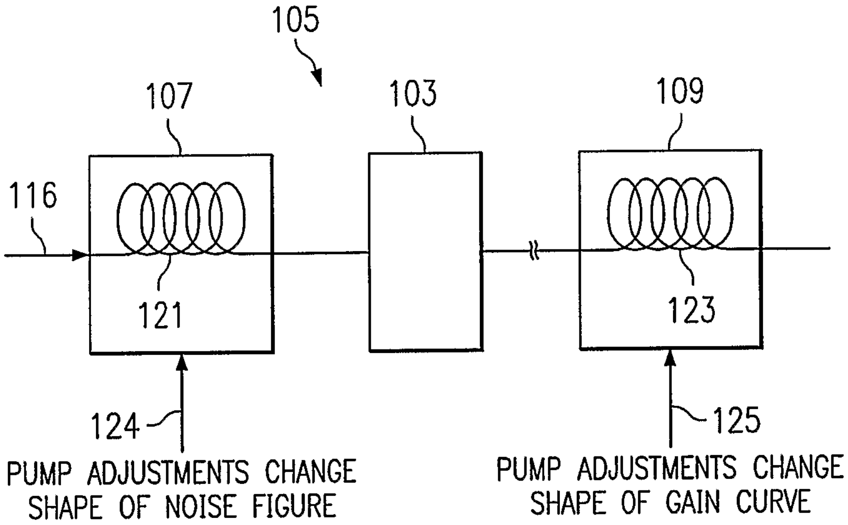

105
107
103
109
116
121
123
124
125
PUMP ADJUSTMENTS CHANGE SHAPE OF NOISE FIGURE
PUMP ADJUSTMENTS CHANGE SHAPE OF GAIN CURVE

FIG. 3b

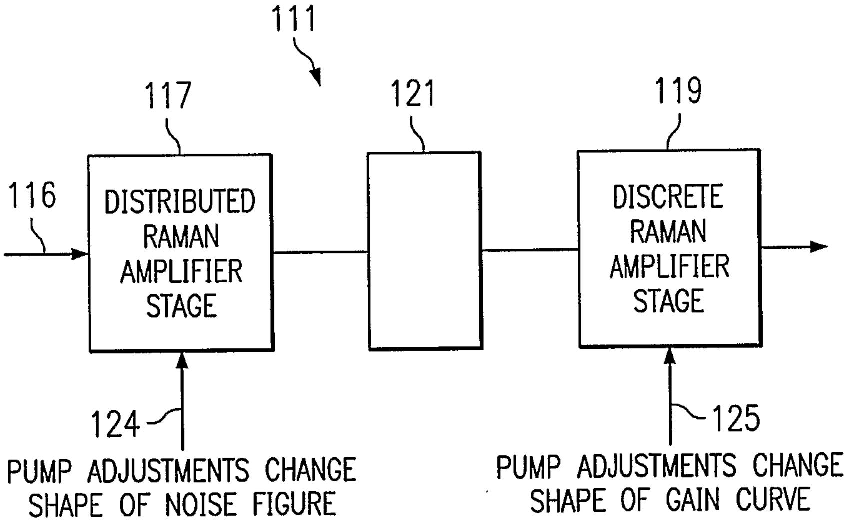
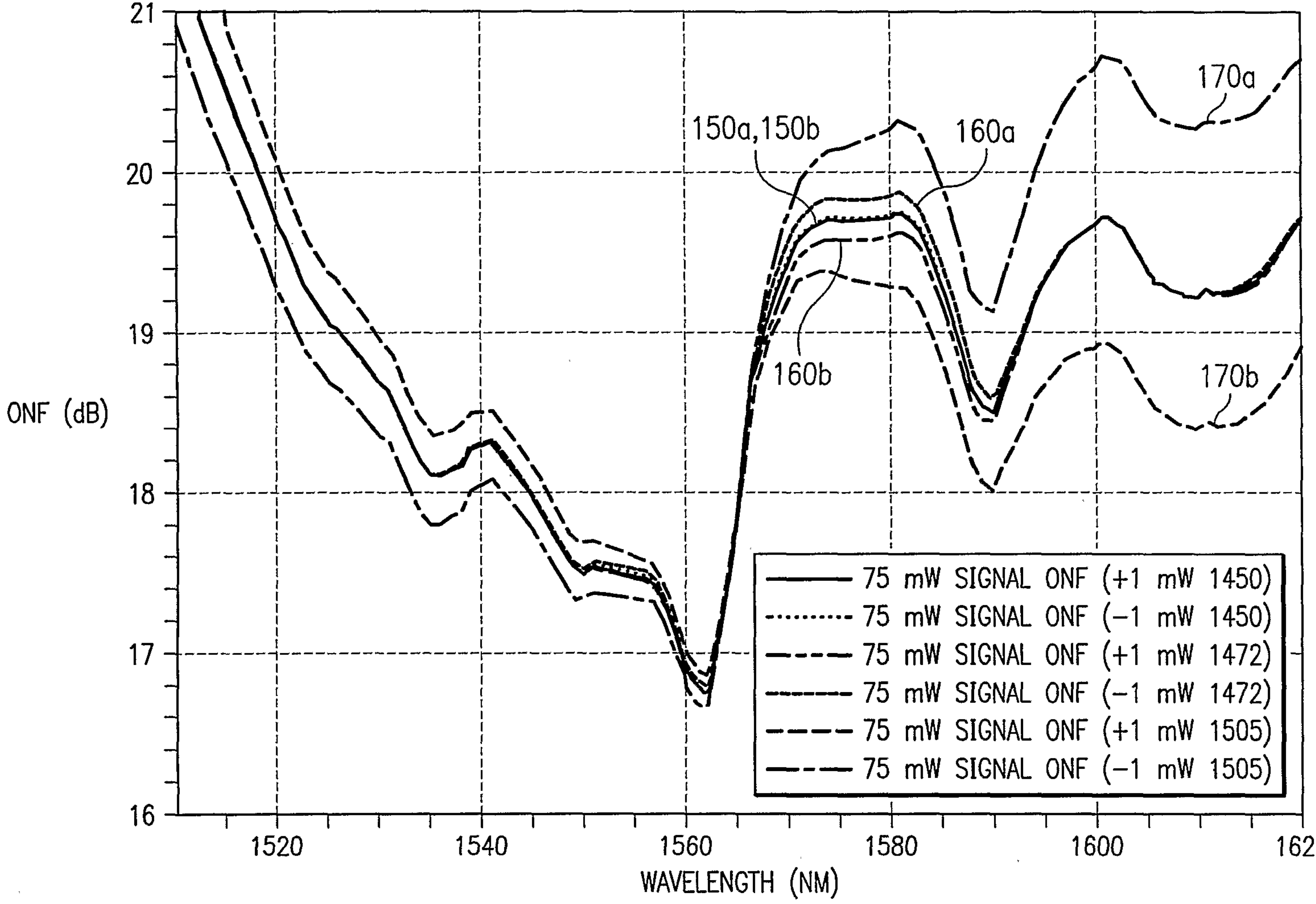

111
117
121
119
116
DISTRIBUTED RAMAN AMPLIFIER STAGE
DISCRETE RAMAN AMPLIFIER STAGE
124
125
PUMP ADJUSTMENTS CHANGE SHAPE OF NOISE FIGURE
PUMP ADJUSTMENTS CHANGE SHAPE OF GAIN CURVE

FIG. 3c

FIG. 2



AMPLIFIER ONF vs 1450, 1472, AND 1505 NM PUMP POWER

FIG. 4a

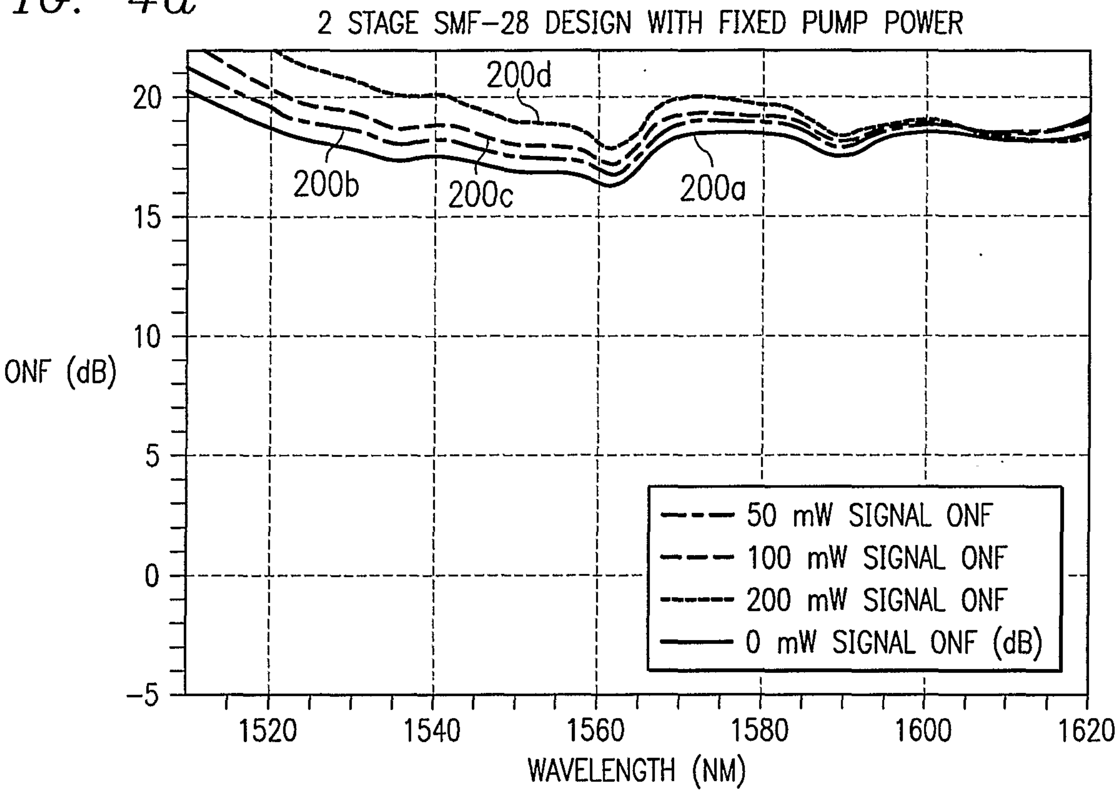

2 STAGE SMF-28 DESIGN WITH FIXED PUMP POWER
200d
200b
200c
200a
ONF (dB)
20
15
10
5
0
−5
1520
1540
1560
1580
1600
1620
WAVELENGTH (NM)
50 mW SIGNAL ONF
100 mW SIGNAL ONF
200 mW SIGNAL ONF
0 mW SIGNAL ONF (dB)

FIG. 4b

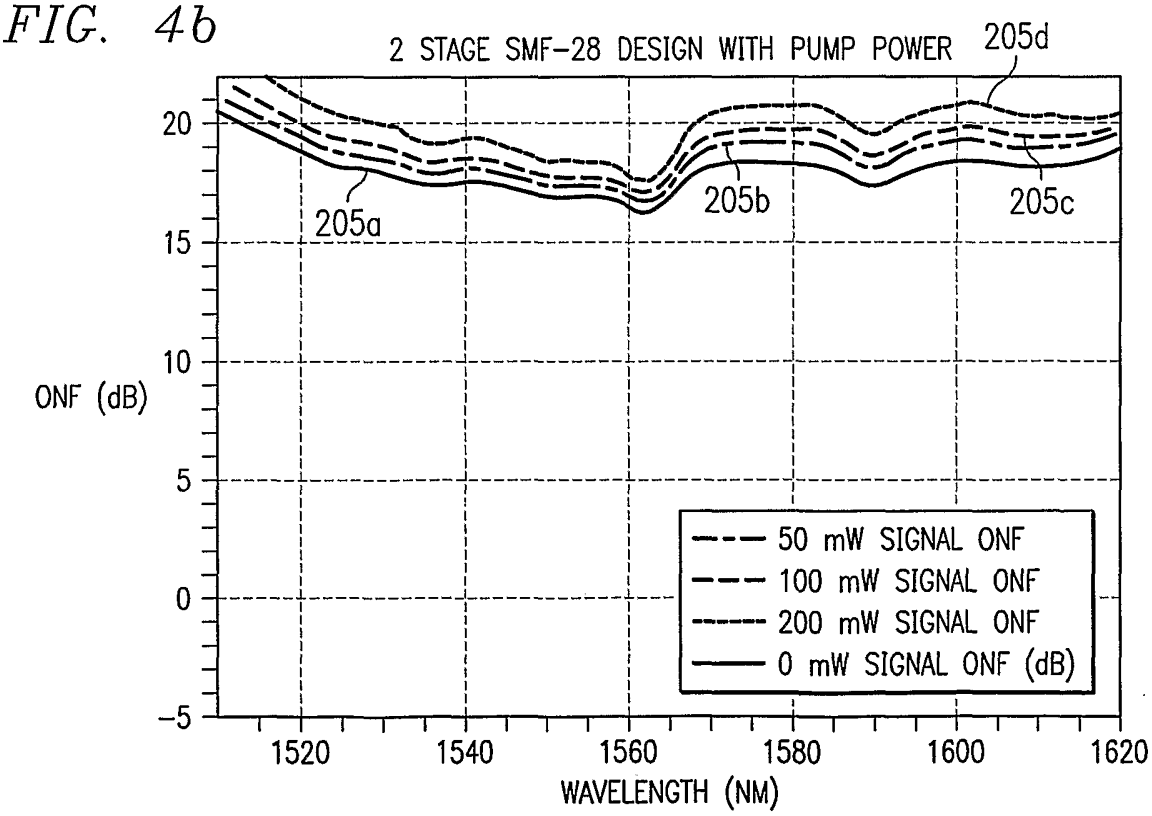

2 STAGE SMF-28 DESIGN WITH PUMP POWER
205d
205a
205b
205c
ONF (dB)
20
15
10
5
0
−5
1520
1540
1560
1580
1600
1620
WAVELENGTH (NM)
50 mW SIGNAL ONF
100 mW SIGNAL ONF
200 mW SIGNAL ONF
0 mW SIGNAL ONF (dB)

FIG. 4c

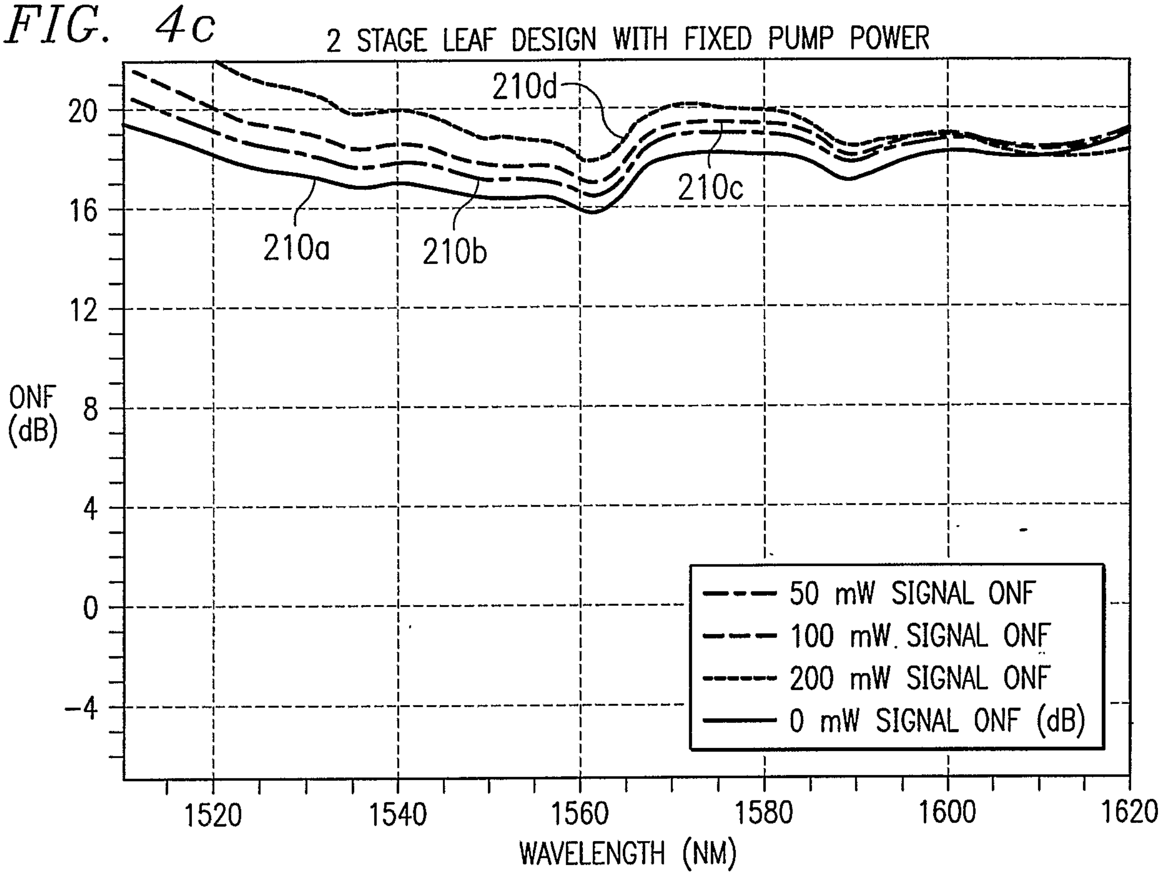

2 STAGE LEAF DESIGN WITH FIXED PUMP POWER
210d
210c
210a
210b
ONF (dB)
20
16
12
8
4
0
−4
1520
1540
1560
1580
1600
1620
WAVELENGTH (NM)
50 mW SIGNAL ONF
100 mW SIGNAL ONF
200 mW SIGNAL ONF
0 mW SIGNAL ONF (dB)

FIG. 4d

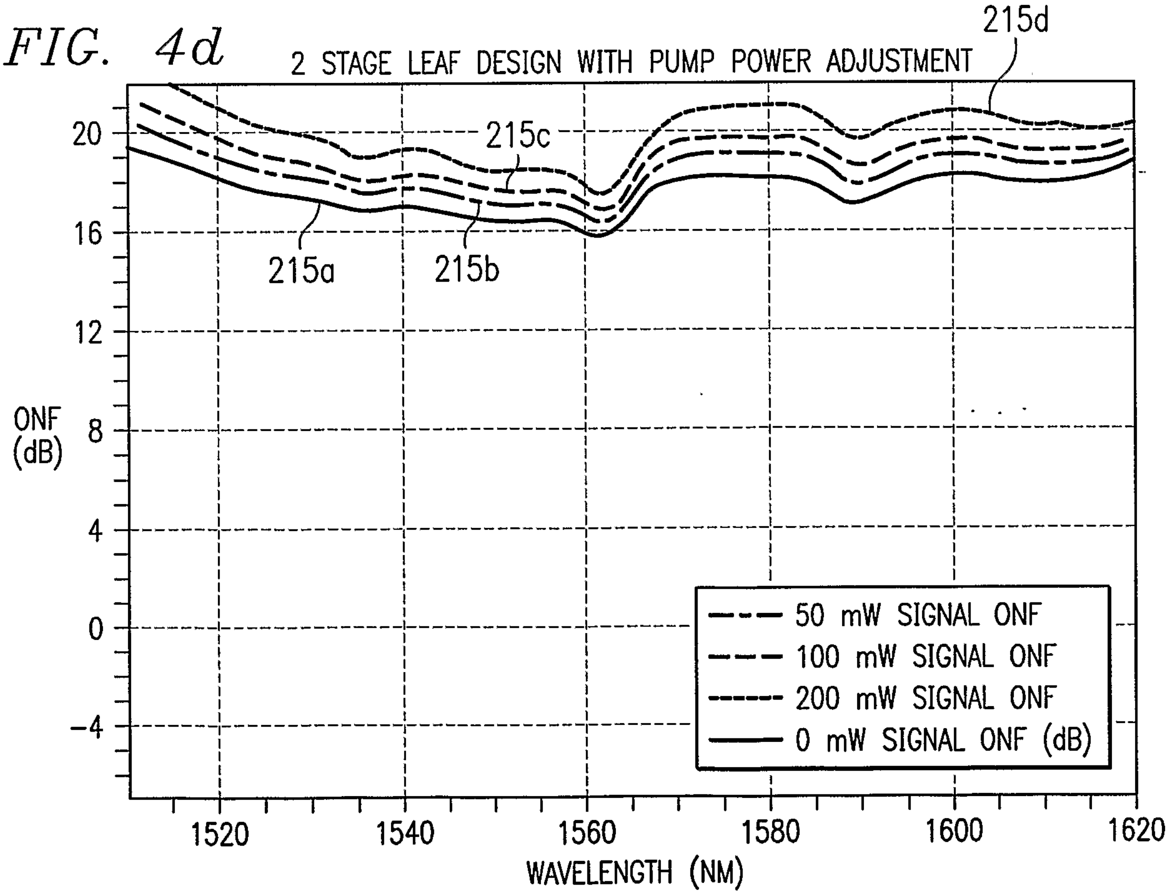

2 STAGE LEAF DESIGN WITH PUMP POWER ADJUSTMENT
215d
215c
215a
215b
ONF (dB)
20
16
12
8
4
0
−4
1520
1540
1560
1580
1600
1620
WAVELENGTH (NM)
50 mW SIGNAL ONF
100 mW SIGNAL ONF
200 mW SIGNAL ONF
0 mW SIGNAL ONF (dB)

FIG. 4e

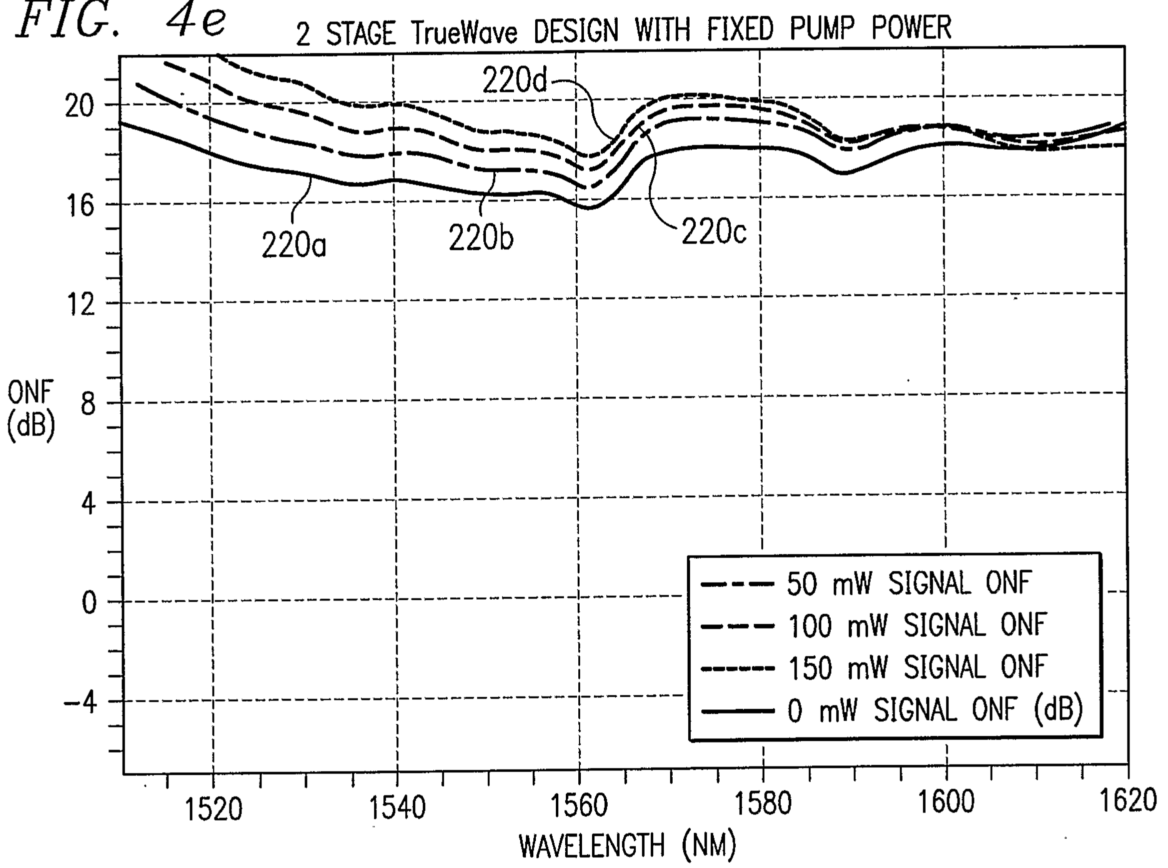
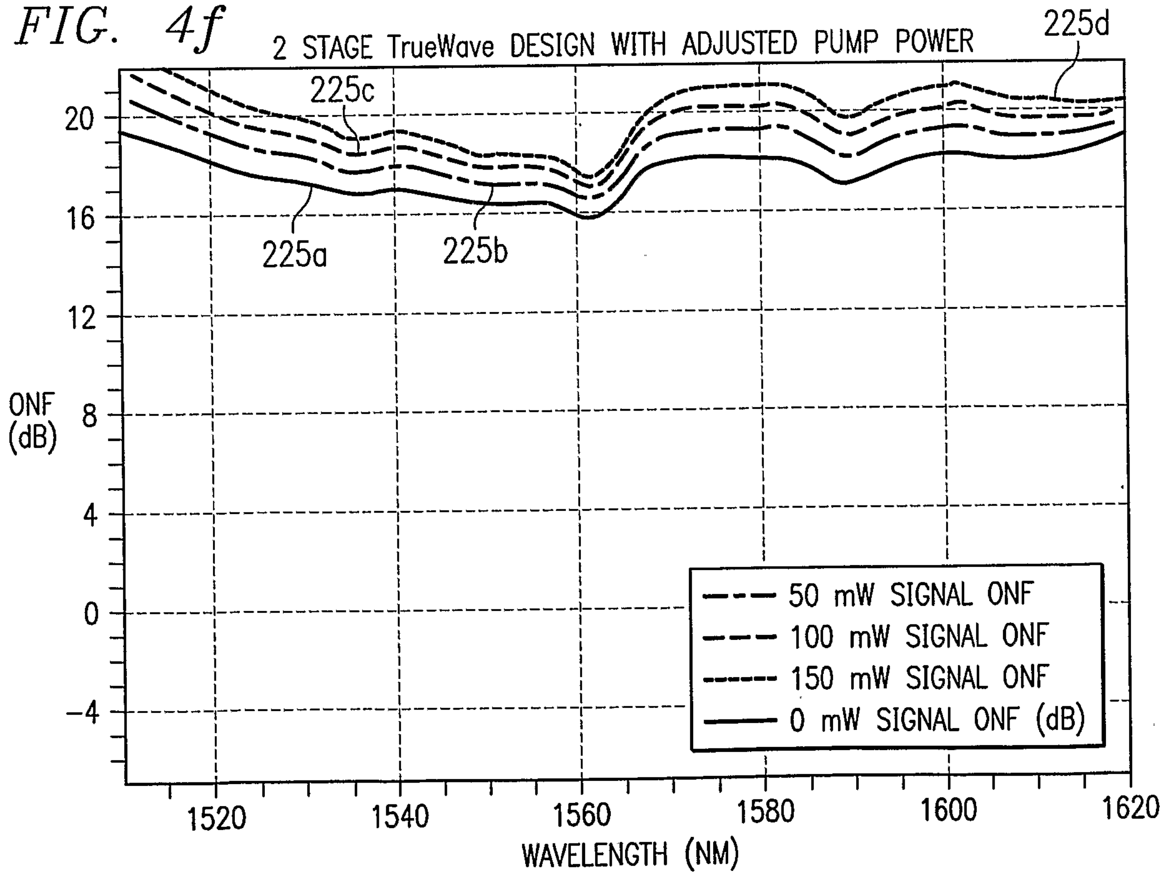

2 STAGE TrueWave DESIGN WITH FIXED PUMP POWER
220d
220a
220b
220c
ONF (dB)
20
16
12
8
4
0
−4
1520
1540
1560
1580
1600
1620
WAVELENGTH (NM)
50 mW SIGNAL ONF
100 mW SIGNAL ONF
150 mW SIGNAL ONF
0 mW SIGNAL ONF (dB)

FIG. 4f


2 STAGE TrueWave DESIGN WITH ADJUSTED PUMP POWER
225d
225c
225a
225b
ONF (dB)
20
16
12
8
4
0
−4
1520
1540
1560
1580
1600
1620
WAVELENGTH (NM)
50 mW SIGNAL ONF
100 mW SIGNAL ONF
150 mW SIGNAL ONF
0 mW SIGNAL ONF (dB)

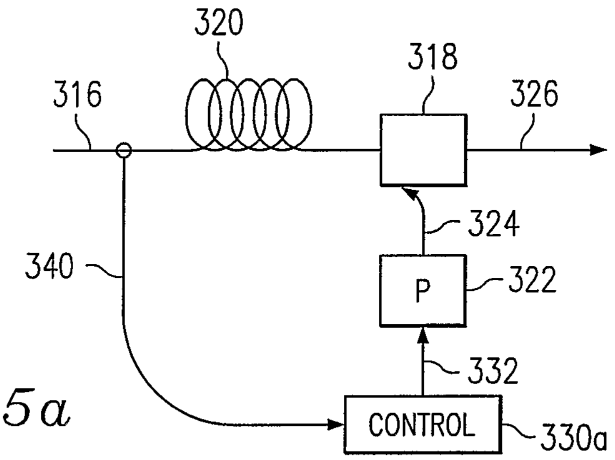


FIG. 5a

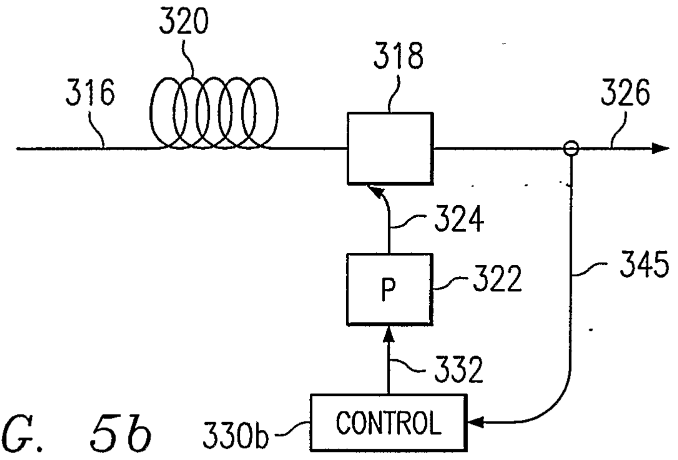


FIG. 5b

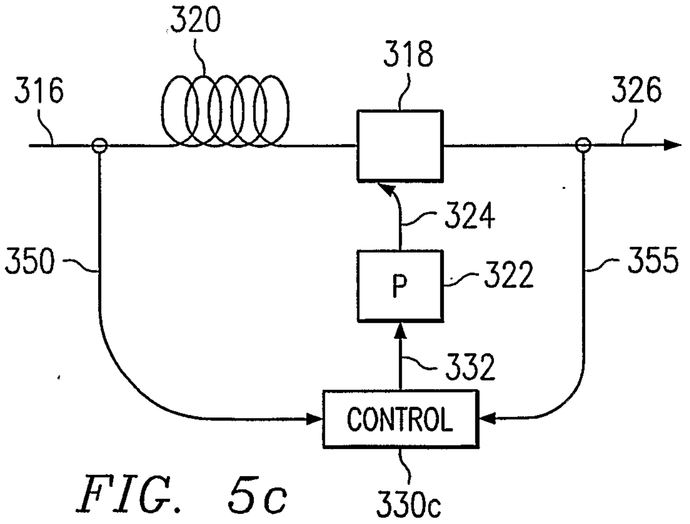
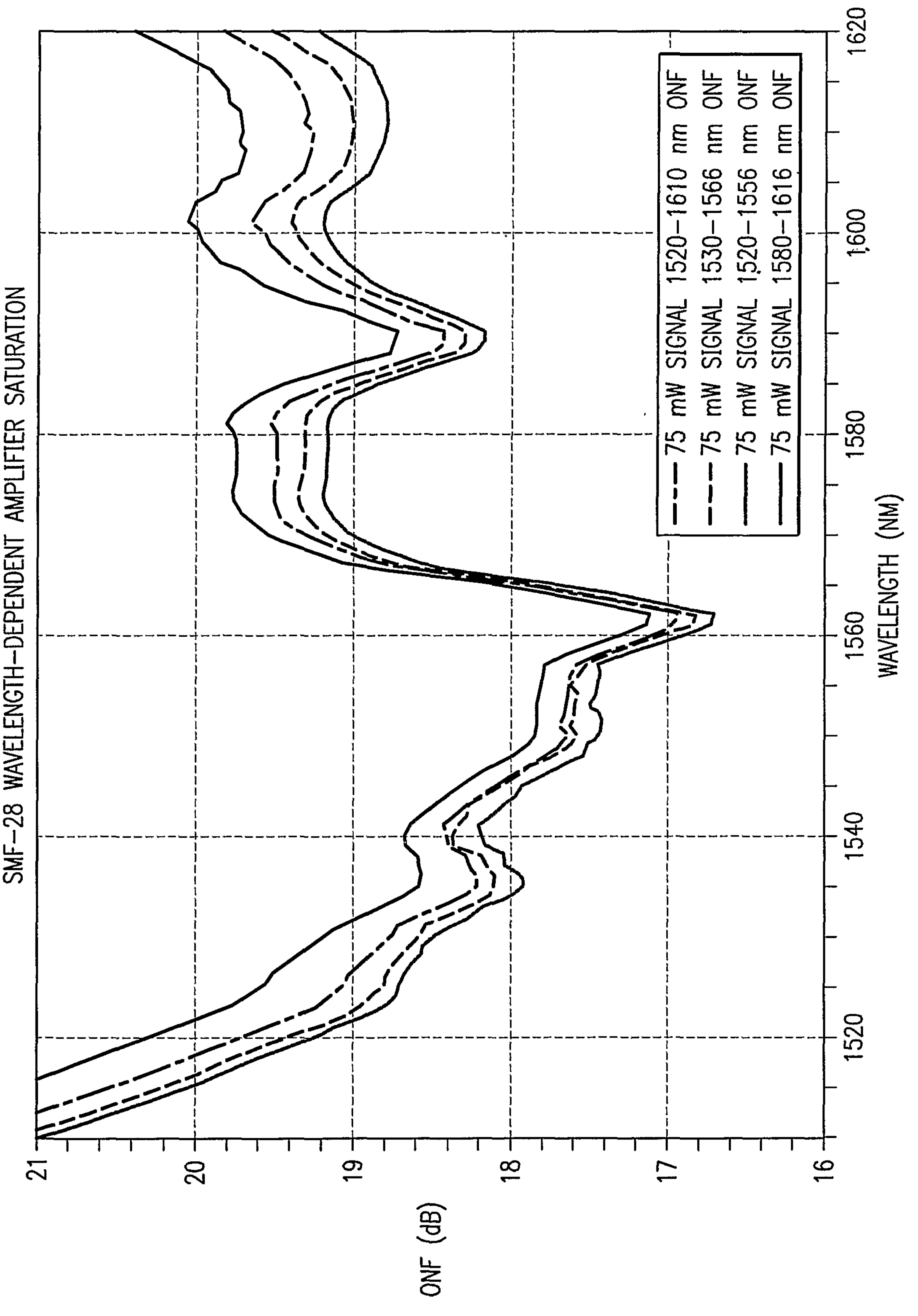


FIG. 5c

FIG. 6



SMF-28 WAVELENGTH-DEPENDENT AMPLIFIER SATURATION

FIG. 7a

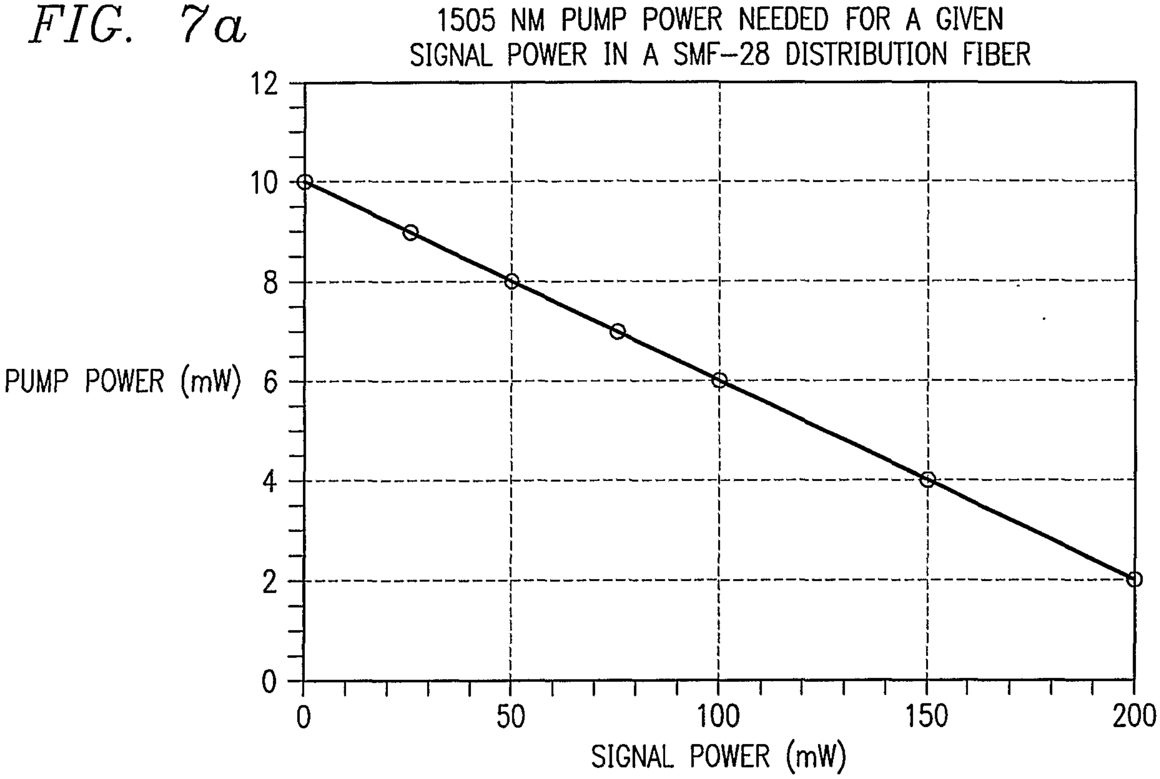

1505 NM PUMP POWER NEEDED FOR A GIVEN
SIGNAL POWER IN A SMF-28 DISTRIBUTION FIBER
PUMP POWER (mW)
0
2
4
6
8
10
12
SIGNAL POWER (mW)
0
50
100
150
200

FIG. 7b

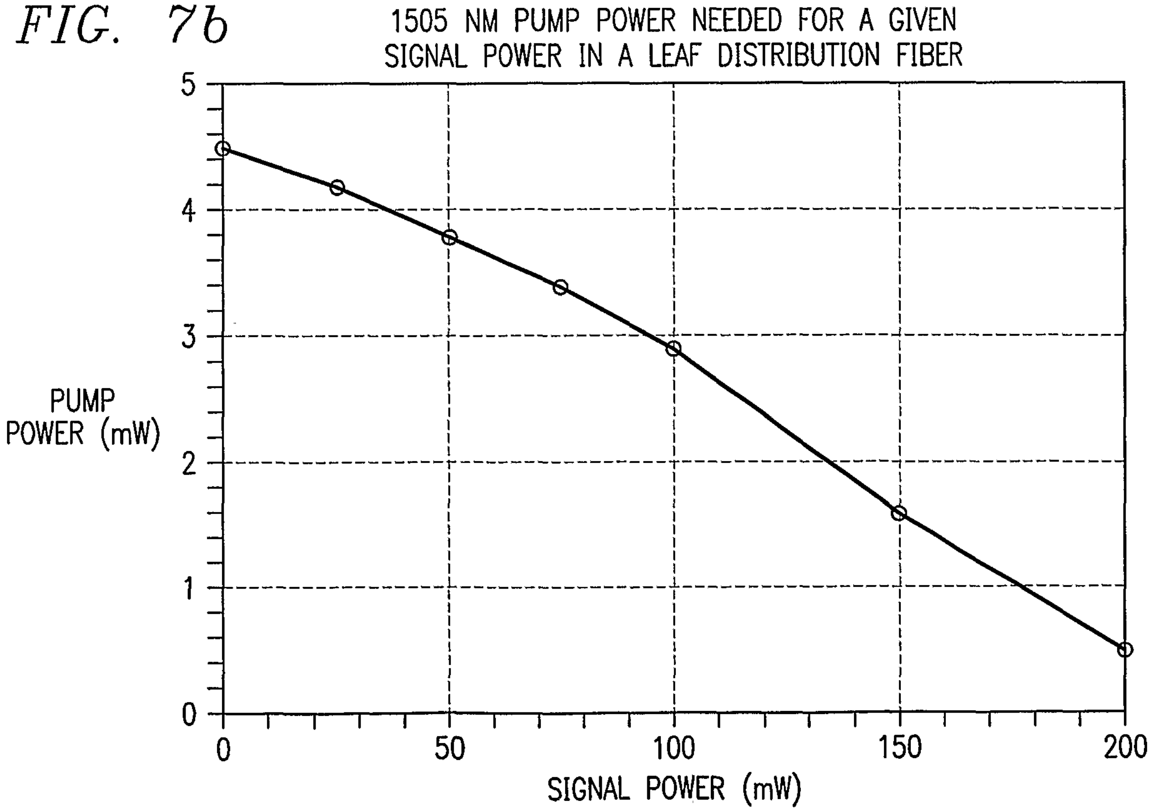

1505 NM PUMP POWER NEEDED FOR A GIVEN
SIGNAL POWER IN A LEAF DISTRIBUTION FIBER
PUMP POWER (mW)
0
1
2
3
4
5
SIGNAL POWER (mW)
0
50
100
150
200

FIG. 7c

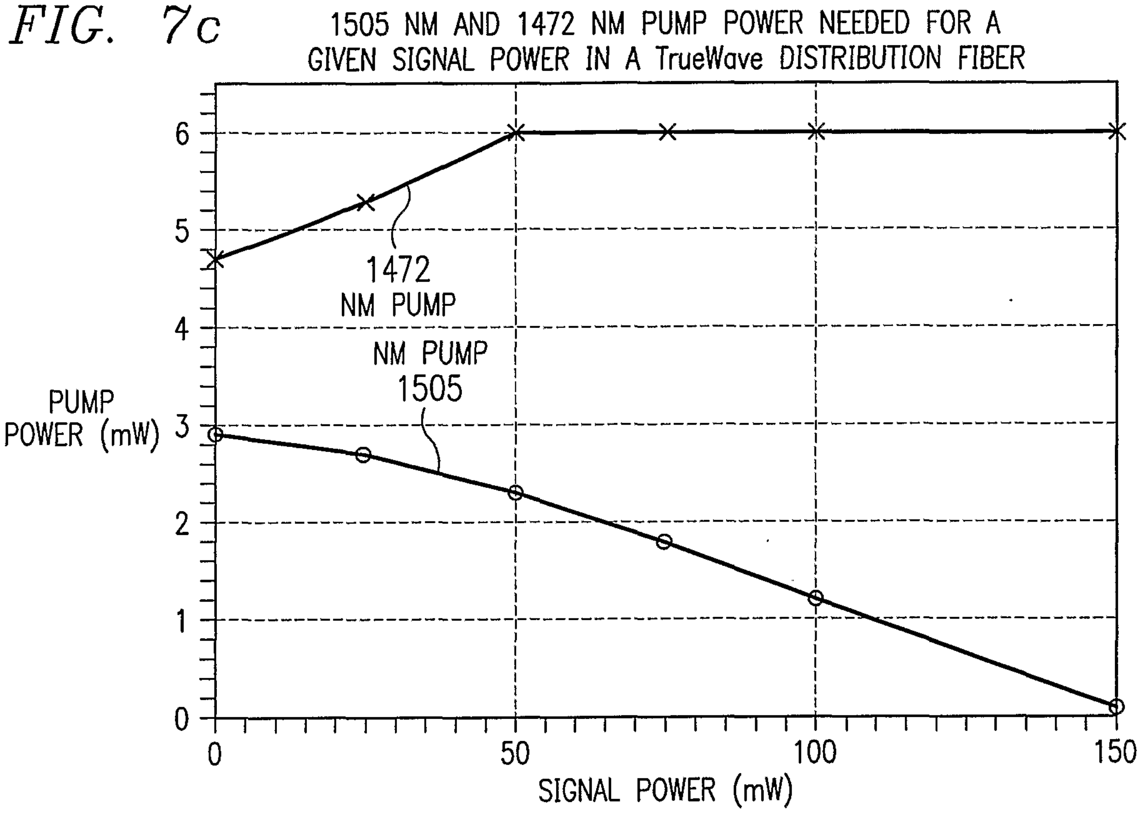
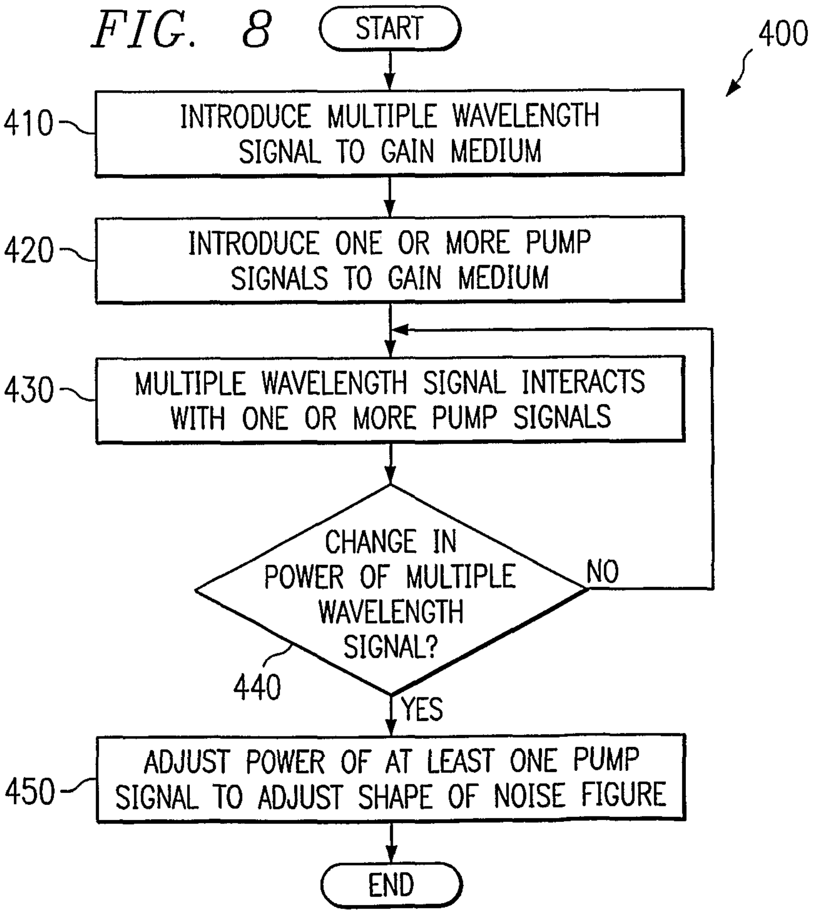

1505 NM AND 1472 NM PUMP POWER NEEDED FOR A GIVEN SIGNAL POWER IN A TrueWave DISTRIBUTION FIBER
PUMP POWER (mW)
6
5
4
3
2
1
0
0
50
100
150
SIGNAL POWER (mW)
1472 NM PUMP
NM PUMP 1505

FIG. 8


START
400
410
INTRODUCE MULTIPLE WAVELENGTH SIGNAL TO GAIN MEDIUM
420
INTRODUCE ONE OR MORE PUMP SIGNALS TO GAIN MEDIUM
430
MULTIPLE WAVELENGTH SIGNAL INTERACTS WITH ONE OR MORE PUMP SIGNALS
CHANGE IN POWER OF MULTIPLE WAVELENGTH SIGNAL?
NO
440
YES
450
ADJUST POWER OF AT LEAST ONE PUMP SIGNAL TO ADJUST SHAPE OF NOISE FIGURE
END