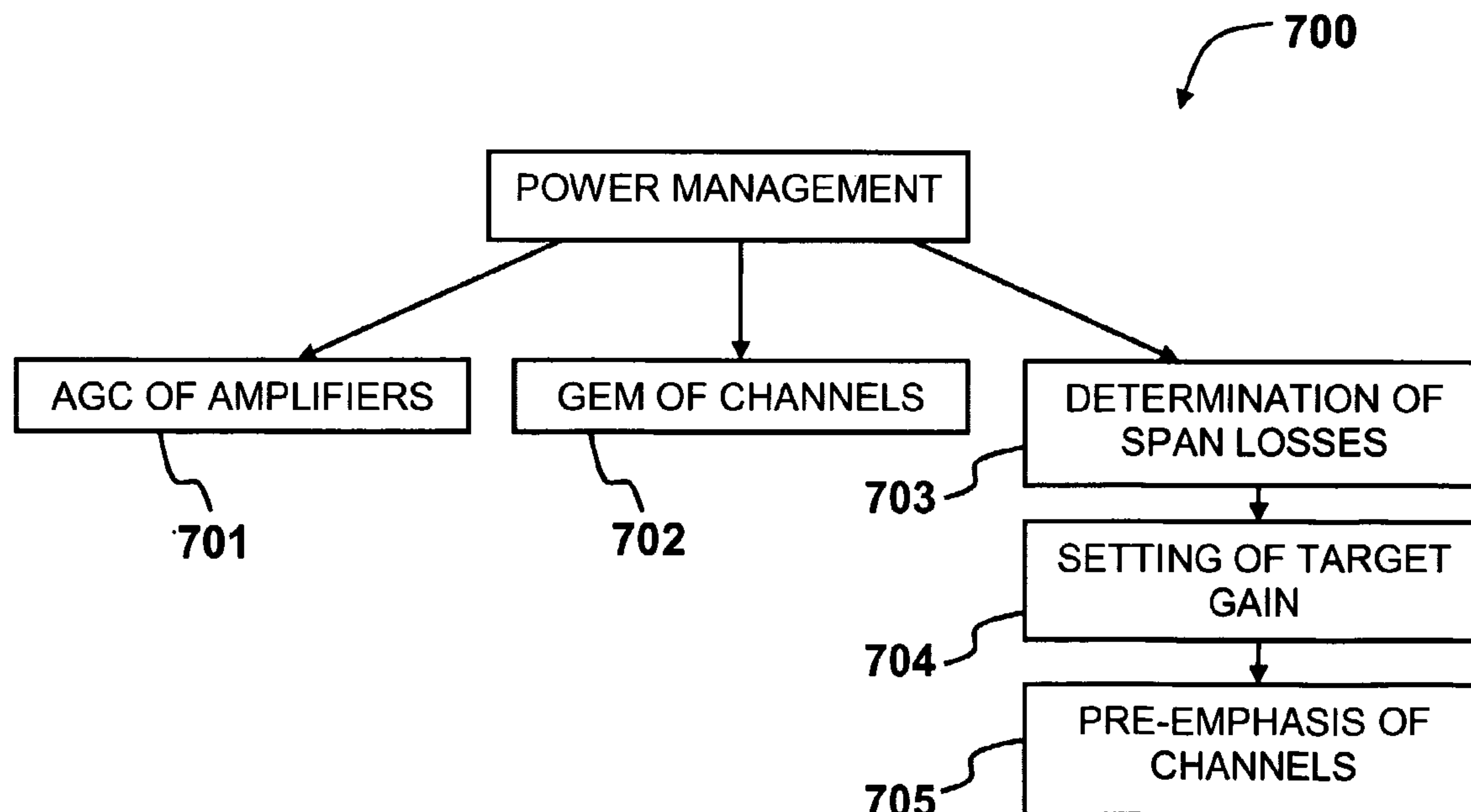




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(54) Title: METHOD AND SYSTEM FOR MULTI-LEVEL POWER MANAGEMENT OF AN OPTICAL NETWORK INCLUDING AUTOMATIC INITIALIZATION



(57) Abrégé/Abstract:

A method and system for multi-level power management in an optical network is provided that may also perform automatic initialization of the network. The power management provides three levels of control of an amplifier in the optical network. The first level of control maintains the gain of the amplifier operating in automatic gain control (AGC) mode at a target amplifier gain. The second level of control eliminates channel gain excursion by dynamically changing the amplifier target gain so as to provide that the gain for each channel is within a gain ripple of the amplifier. The third level of control sets the target gains of amplifiers according to fiber span losses. The third level of control may also perform pre-emphasis of channel powers by changing the power of one or more channels passing through the amplifier so as to compensate for gain ripple of the amplifier. As a result, this multi-level control of the amplifiers in the network provides an increased level of optical signal to noise ratio (OSNR), protection of network components, and stabilization of channel power in the network.



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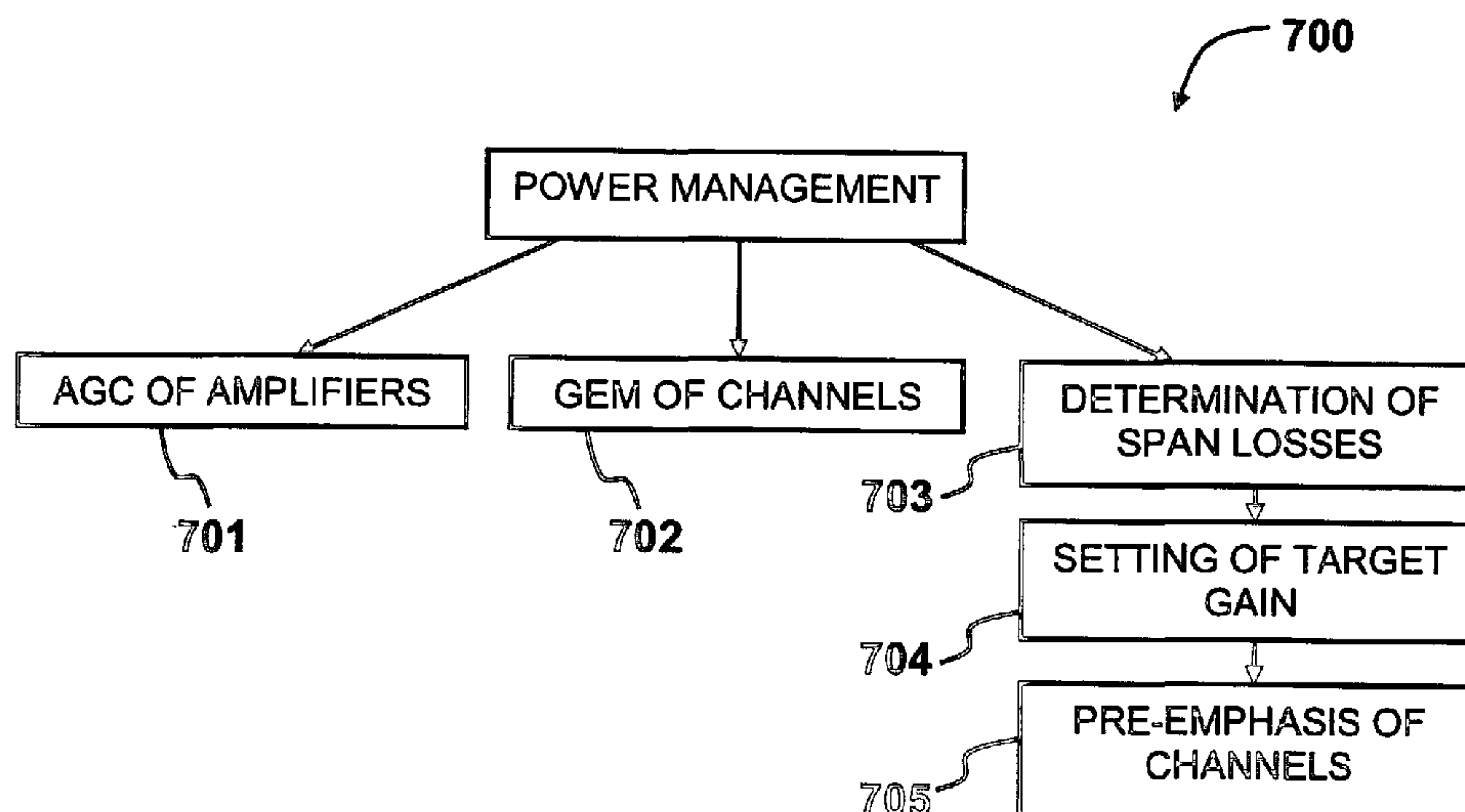
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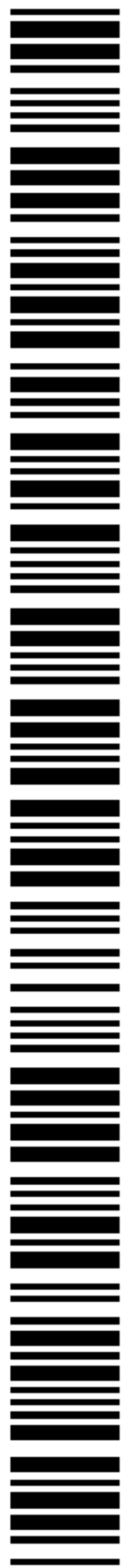
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(54) Title: METHOD AND SYSTEM FOR MULTI-LEVEL POWER MANAGEMENT OF AN OPTICAL NETWORK INCLUDING AUTOMATIC INITIALIZATION



(57) Abstract: A method and system for multi-level power management in an optical network is provided that may also perform automatic initialization of the network. The power management provides three levels of control of an amplifier in the optical network. The first level of control maintains the gain of the amplifier operating in automatic gain control (AGC) mode at a target amplifier gain. The second level of control eliminates channel gain excursion by dynamically changing the amplifier target gain so as to provide that the gain for each channel is within a gain ripple of the amplifier. The third level of control sets the target gains of amplifiers according to fiber span losses. The third level of control may also perform pre-emphasis of channel powers by changing the power of one or more channels passing through the amplifier so as to compensate for gain ripple of the amplifier. As a result, this multi-level control of the amplifiers in the network provides an increased level of optical signal to noise ratio (OSNR), protection of network components, and stabilization of channel power in the network.



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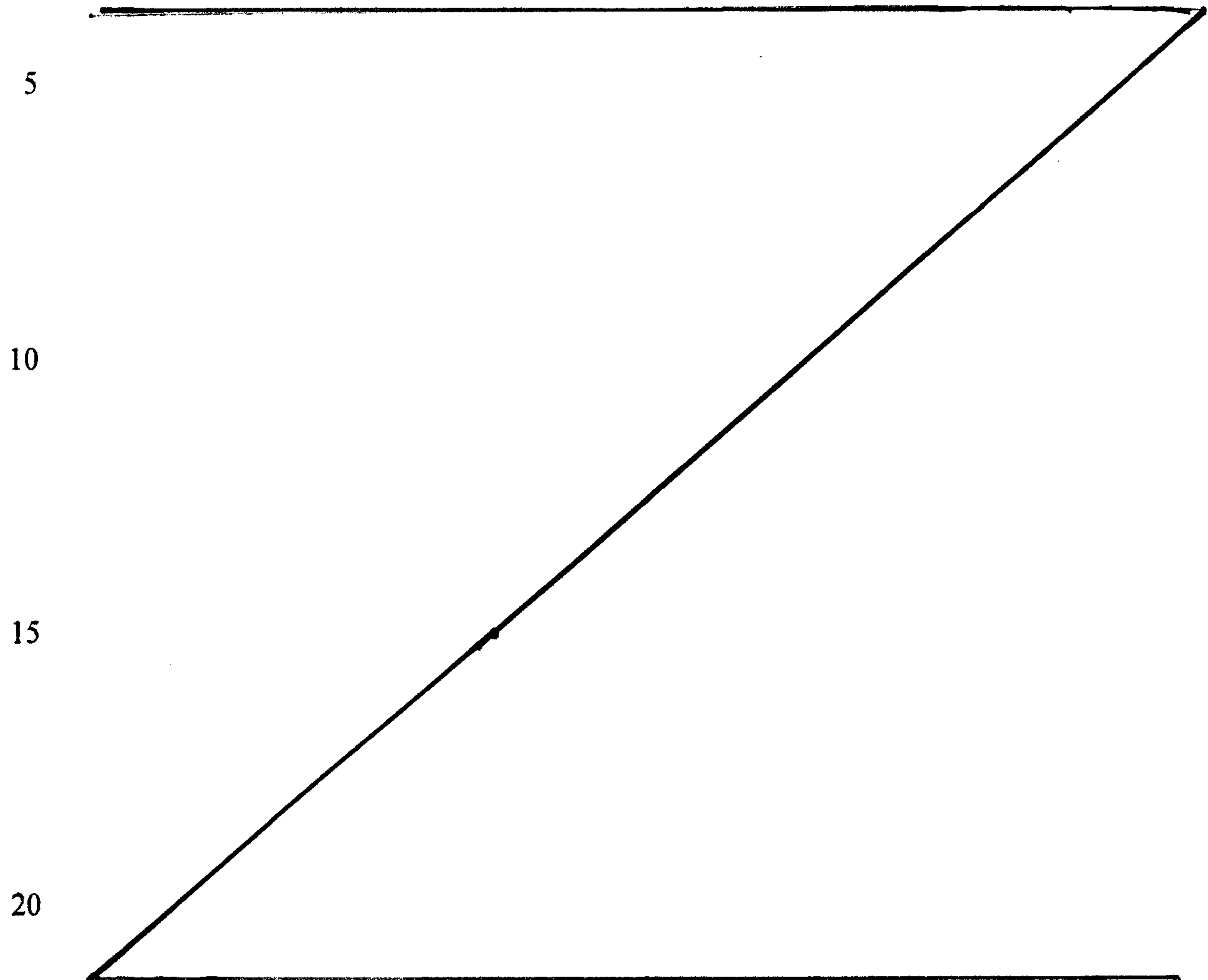
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METHOD AND SYSTEM FOR MULTI-LEVEL POWER MANAGEMENT
OF AN OPTICAL NETWORK INCLUDING AUTOMATIC INITIALIZATION



FIELD OF THE INVENTION

25 The present invention relates generally to optical networks, and in particular to a method and system for multi-level power management of an optical network including automatic initialization of the network.

BACKGROUND OF THE INVENTION

30 The objectives of power management in optical networks depend on many factors, including the distance covered by a network and the transmission speed of the

network. Long-haul networks have generally been designed to maximize and maintain transmission power of optical channels at the required level over long distances and fairly stable configurations of the network. However, the focus of
5 smaller, for example metropolitan area networks (MANs), is shifting towards supporting the dynamic adding and dropping of channels due to network upgrades and reconfigurations, which cause frequent variation in optical power levels and therefore requires dynamic and comprehensive power
10 management in an optical network.

Several different approaches to power management in an optical network are currently available. Power management of optical components, such as optical amplifiers, using an electronic variable optical attenuator
15 (eVOA) and a controller provides local control of the component. Unfortunately, the local control of the component does not take into account larger-scale information regarding network configuration and conditions, and hence has inherent drawbacks.

20 Another known approach to power management is the use of dynamic gain equalizers (DGEs) to reduce variations of channel optical power in the network. However, for short distances, such as in metropolitan/regional networks, the use of DGEs is not an economically attractive option.

25 Comprehensive power management includes initialization of the network to desired operating parameters. Currently, a typical initialization of an optical network is performed manually. This process requires slow and time-consuming on site configuration involving
30 costly personnel and, most significantly, it is prone to human errors.

U.S. Patent No. 6,304,347 to Beine et al. issued Oct. 16, 2001 and entitled "Optical Power Management in an Optical Network" discloses a system for managing an optical network such that selected power characteristics in the network are achieved by configuring optical amplifiers and/or variable optical attenuators within the nodes of a network. The focus of the system is to manage the power characteristics of the nodes of a protected network during switching events. To this end, Switching and Wavelength Manager Modules may provide switching and wavelength management information to each node, or the nodes may exchange information between themselves to distribute management information to perform the switching and maintain the power characteristics. The patent also discloses that as part of the managing process, a Power Management Module may determine power parameters at the input and output edges of a card and store these power parameters in a parameter table. Each of the modules described in Patent No. 6,304,347 requires additional logic, communications connections, and memory for parameter tables. In summary, methods described in this patent are specific to protected networks, which undergo switching events that change the configuration of the optical network. As a result, they require re-configuring of nodes of the network until the optical network has the selected power characteristics, which is complicated and time-consuming.

Therefore, there is a need in industry for the development of an improved method for effective, comprehensive, and accurate power management in an optical network which would include automatic initialization to provide required operating conditions for the network.

SUMMARY OF THE INVENTION

Therefore there is an object of the invention to provide a method and system for multi-level power management of an optical network including automatic initialization
5 that would avoid or minimize the above-mentioned drawbacks.

According to one aspect of the invention there is provided a method for automatic multi-level power management in an optical network, comprising multi-level control of an amplifier, including the steps of:

- 10 (i) automatically determining span losses in the network comprising the amplifier (third level control);
- (ii) setting a target gain of the amplifier to be equal to the span loss of the fiber span immediately following the amplifier (first level control); and
- 15 (iii) regulating the amplifier gain so as to be equal to said target gain (second level control).

The method for multi-level power management of an optical network may conveniently include automatic initialization of the network, comprising the steps of:

- 20 (a) providing a multi-level control of the amplifier, including:
 - (i) automatically determining a span loss of each fiber span in the network;
 - (ii) setting a target gain of the
25 amplifier to be equal to a span loss of the fiber span immediately following the amplifier;
 - (iii) regulating the amplifier gain so as to be equal to said target gain;
 - (iv) dynamically changing said target
30 gain of the amplifier so as to provide that a gain

of a channel passing through the amplifier is within a predetermined gain range; and

(b) changing power of one or more channels passing through the amplifier so as to provide that power variation for the channels passing through the amplifier is within a predetermined power range.

The step (a) of automatically determining the span loss may comprise:

(c) selecting a channel on the optical link and turning on the channel power at the corresponding transmitter;

(d) increasing the power at said transmitter until the signal power level at the amplifier nearest to said transmitter reaches a predetermined power level;

(e) varying a target gain of said amplifier until the signal power level at the network element nearest to the amplifier reaches said predetermined power level;

(f) repeating the step (e) until the signal power level at all network elements on the optical link reaches the same said predetermined power level;

(g) determining the span loss of each fiber span as being equal to the following value:

the difference between the power at the transmitter in the step (d) and said predetermined power level, if the fiber span is located between said transmitter and the optical amplifier nearest to the transmitter; and the target gain of the amplifier immediately preceding the fiber span, the target gain being set in the step (e), if the fiber span is any of the remaining spans of fiber.

Alternatively, the step (a) of automatically determining the span loss may comprise:

determining a signal power level at an input of a fiber span in the optical link;

determining a signal power level at an output of the fiber span in the optical link; and

5 determining the loss for the fiber span to be equal to the difference between said signal power level at the input of the fiber span and said signal power level at the output of the fiber span.

10 Additionally, the step (iv) of dynamically changing the target gain of the amplifier may comprise changing the target gain of the amplifier so as to provide that the gain of a channel passing through the amplifier is within the predetermined gain range defined as the gain ripple of the amplifier, the gain ripple being a variation
15 of the amplifier gain profile with channel wavelength.

Furthermore, the step (b) of changing the power may further comprise changing the power of one or more channels passing through the amplifier so as to provide that the power variation for the channels passing through the
20 amplifier is opposite to the cumulative gain ripple of the amplifiers in the link so as to compensate for the cumulative gain ripple, the cumulative gain ripple of the amplifiers being a variation of the amplifiers cumulative gain profile with channel wavelength.

25 In a modification to the embodiments of the invention, the method for automatic multi-level power management in an optical network, comprises the steps of providing a multi-level control of the amplifier, including:

(i) automatically determining span losses;

(ii) setting a target gain of the amplifier to be equal to a span loss of the fiber span immediately following the amplifier;

(iii) regulating the amplifier gain so as to be
5 equal to said target gain; and

(iv) dynamically changing said target gain of the amplifier so as to ensure that a gain of a channel passing through the amplifier is within a predetermined gain range.

The step (iv) of dynamically changing the target
10 gain of the amplifier may comprise changing the target gain of the amplifier so as to provide that the gain of a channel passing through the amplifier is within the predetermined gain range defined as the gain ripple of the amplifier, the gain ripple being a variation of the amplifier gain profile
15 with channel wavelength.

In another modification to the embodiments of the invention, the method for automatic multi-level power management in an optical network, comprises the steps of:

(a) providing a multi-level control of the
20 amplifier, including:

(i) automatically determining span
losses;

(ii) setting a target gain of the
amplifier to be equal to a span loss of the fiber
25 span immediately following the amplifier;

(iii) regulating the amplifier gain so
as to be equal to said target gain; and

(b) changing power of one or more channels passing
through the amplifier so as to provide that power variation
30 for the channels passing through the amplifier is within a
predetermined power range.

The step (b) of changing the power may further comprise changing the power of one or more channels passing through the amplifier so as to provide that the power variation for the channels passing through the amplifier is
5 opposite to the cumulative gain ripple of the amplifiers in the link so as to compensate for the cumulative gain ripple, the cumulative gain ripple of the amplifiers being a variation of the amplifiers cumulative gain profile with channel wavelength.

10 The step (iv) of dynamically changing the target gain of the amplifier may comprise the steps of:

determining a gain of an optical channel of the plurality of optical channels to be amplified in the amplifier;

15 selecting a sub-set of optical channels from the plurality of optical channels; and

dynamically regulating a target gain of the amplifier in response to the changes of the gain of said optical channel of the plurality of optical channels so as
20 to provide that the gain for each optical channel from the selected sub-set of channels is within a predetermined range.

The step of selecting may comprise selecting the sub-set of channels including one channel only or including
25 all channels of the plurality of channels to be amplified.

Additionally, the step of dynamically regulating the target gain of the amplifier may comprise regulating the target gain of the amplifier so as to provide that the gain for each optical channel from the selected sub-set of
30 channels is within a gain ripple Δ of the amplifier, the

gain ripple Δ being a variation of the amplifier gain profile within a range of wavelengths to be amplified or within a band of wavelengths to be amplified.

In the first embodiment of the invention, the step
5 of dynamically regulating the target gain of the amplifier further comprises:

(a) identifying an optical channel over the band of wavelengths that carries a signal and has the lowest gain; and

10 (b) changing the target gain of the amplifier so as to provide that the gain of said channel is substantially equal to the following value $G_{\text{ripple min}} = G_0 - \Delta/2$, wherein G_0 is an original target gain of the amplifier.

If required, the step (b) of changing the target
15 gain may comprise changing the target gain so as to provide that the gain of said channel is equal to $G_{\text{ripple min}}$.

Additionally, the method may further comprise the following steps:

(c) identifying all optical channels over the band
20 of wavelengths that carry a signal;

(d) calculating an average gain G_{avg} of said channels that carry a signal;

(e) calculating a gain difference: $G_{\text{diff}} = G_{\text{ripple min}} - G_{\text{min sig}}$, wherein $G_{\text{min sig}}$ is the gain of the channel that
25 carries a signal and has the lowest gain, the steps (c), (d), and (e) being performed before step (b); and

wherein the step (b) comprises the step of (f) changing the target gain of the amplifier so as to be substantially equal the following value: $G_{\text{target}} = G_{\text{avg}} + G_{\text{diff}}$.

If required, the step (f) of changing the target gain may comprise changing the target gain so as to be equal to G_{target} .

In a modification to the method of the first
5 embodiment of the invention, the step of dynamically regulating the target gain of the amplifier further comprises:

(a) identifying an optical channel over the band of wavelengths that has the lowest gain;

10 (b) identifying an optical channel over the band of wavelengths that carries a signal;

(c) calculating a gain difference: $G_{diff} = G_{sig} - G_{min}$ gain, wherein G_{min} gain is the channel that has the lowest gain and G_{sig} is the channel that carries a signal identified
15 in (b); and

(d) changing the target gain of the amplifier so as to provide that the gain of the channel that carries a signal is substantially equal to the following value:
 $G_{recalculated} = G_0 - \Delta/2 + G_{diff}$, wherein G_0 is an original target
20 gain of the amplifier.

If required, the step (d) of changing the target gain may comprise changing the target gain so as to provide that the gain of said channel is equal to $G_{recalculated}$.

Additionally, the method may further comprise:

25 (e) identifying all optical channels over the band of wavelengths that carry a signal;

(f) calculating an average gain G_{avg} of said channels;

(g) calculating a gain difference $\tilde{G}_{diff} = G_{recalculated} - G_{sig}$, the steps (e), (f), and (g) being performed before
30 step (d); and

wherein the step (d) comprises the step of (h) changing the target gain of the amplifier so as to be substantially equal to the following value:

$$G_{target} = G_{avg} + \tilde{G}_{diff}.$$

5 If required, the step (h) of changing the target gain may comprise changing the target gain so as to be equal to G_{target} .

In the second embodiment of the invention, the step of dynamically regulating the target gain of the
10 amplifier further comprises:

identifying all optical channels over the band of wavelengths that carry a signal, including determining the number of said channels $N_{populated\ channels}$ and determining the gains g_i for each of said channels;

15 calculating weights w_i for said channels, such

that $\sum_1^{N_{ch}} w_i = 1$, wherein N_{ch} is the total number of optical

channels to be amplified by the amplifier; and

changing the target gain of the amplifier so as to be substantially equal to the following value:

20 $G_{weighted\ avg} = \left[\sum_{i=signal\ channels} g_i \cdot w_i \right] \frac{N_{ch}}{N_{signal\ channels}},$ wherein N_{ch} is the total

number of optical channels to be amplified by the amplifier.

If required, the step of changing the target gain may comprise changing the target gain so as to be equal to
25 $G_{weighted\ average}$.

In a modification to the method of the second embodiment, the step of dynamically regulating the target gain of the amplifier further comprises:

identifying all optical channels over the band of wavelengths that carry a signal, including determining the gains g_i for each of said channels and calculating weights w_i of said channels; and

- 5 changing the target gain of the amplifier so as to be substantially equal to the following value:

$$\tilde{G}_{\text{weighted avg}} = \left[\sum_{i=\text{signal channels}} g_i \cdot \tilde{w}_i \right], \text{ wherein } \tilde{w}_i = \frac{w_i}{\sum_{k=\text{signal channels}} w_k} \text{ such that}$$

$$\sum_{i=\text{signal channels}} \tilde{w}_i = 1.$$

- 10 If required, the step of changing the target gain may comprise changing the target gain so as to be equal to $\tilde{G}_{\text{weighted avg}}$.

Additionally, the step of calculating the weights may comprise:

- 15 sorting the optical channels over the band of wavelengths by ascending gain to form an ascending gain profile, which has an ascending channel order as its argument;

- 20 sorting the optical channels over the band of wavelengths by descending gain to form a descending gain profile, which has a descending channel order as its argument;

normalizing the descending gain profile such that

$$g_i' = \frac{g_i}{\sum g_i}; \text{ and}$$

- 25 forming a weight profile as the normalized descending gain profile in which the ascending channel order is used as its argument; and

determining the weights for the channels from the weight profile.

Additionally, the above method may further
comprise:

calculating an average w_{avg} of the weights;

calculating a center wavelength λ_c in the band of
5 wavelengths;

multiplying the weights by the following weight-
adjusting function:

$f(\lambda) = c(\lambda - \lambda_c) + w_{avg}$, wherein c is a negative
constant for adjusting the weight distribution; and

10 normalizing the weights such that $\sum_1^{N_{ch}} w_i = 1$.

According to another aspect of the invention,
there is provided a method for monitoring and controlling an
optical link, comprising the steps of:

determining a gain of an optical channel of the
15 plurality of optical channels to be carried by the optical
link;

selecting a sub-set of optical channels from the
plurality of optical channels; and

dynamically regulating a target gain for the
20 optical link in response to the changes of the gain of said
optical channel of the plurality of optical channels so as
to provide that the gain for each optical channel from the
selected sub-set of channels is within a predetermined
range.

25 According to yet another aspect of the invention,
there is provided a method for automatic initialization of
an optical link in an optical network, comprising the steps
of:

(a) determining a span loss of each fiber span in
30 the link;

(b) setting a target gain of each amplifier in the link based on the span losses of the fiber spans in the link;

(c) selecting an optical channel to be transmitted
5 through the link and turning on the channel power;

(d) setting a signal power level at a transmitter for said channel on the link so that to provide transmittance of said channel through the link while the channel is amplified by the amplifier in the link;

10 (e) setting a signal power level at a receiver for said channel on the link so as to provide that the power level at the receiver is within a predetermined range;

(f) repeating the steps (c) to (e) until all channels to be transmitted through the link are selected.

15 The method described above has been implemented in the third embodiment of the invention.

Alternatively, the step (d) of setting the signal power level at the transmitter may comprise setting the attenuation of an attenuator at the transmitter and the step
20 (e) of setting the signal power level at the receiver may comprise setting the attenuation of an attenuator at the receiver.

Additionally, the step (d) of setting the signal power level at the transmitter may comprise setting the
25 signal power level at the transmitter to be substantially equal to one of the following:

the maximum power $P_{Tx\ max}$ of the transmitter, if the loss L_0 of the fiber span located between the transmitter and the optical amplifier nearest to the transmitter (a
30 first fiber span) is greater than or equal to a minimum span loss L_{min} specified for the network; and

$P_{Tx \max} - L_{\min} + L_0$, if the loss L_0 of said first fiber span is less than the minimum span loss $L_{\min}$.

Also, the step (e) of setting the signal power level at the receiver may comprise setting the signal power level at the receiver to be substantially equal to $P_{Rx \max} - P_{\text{margin}}$, wherein P_{margin} is a specified power margin for the channel and $P_{Rx \max}$ is a maximum specified channel power to the receiver.

Furthermore, the step (b) of setting the target gain of each amplifier may comprise setting the target gain so as to provide that the power at the output of each amplifier is substantially equal to a maximum specified power $P_{\max}$ for a channel in the optical network.

Specifically, the step of setting the target gain of each amplifier may comprise the steps of:

setting a target gain G_1 of the optical amplifier nearest to the transmitter to be substantially equal to the following value:

$$G_1 = (P_{\max} - P_{Tx}) + L_0$$

wherein $P_{\max}$ is the maximum specified power for a channel in the optical network, and P_{Tx} is an average power of the transmitters in the link; and

setting a target gain G_i of each of the remaining amplifiers in the link to be substantially equal to the loss L_i of the fiber span following each of said amplifiers.

If desired, the step (e) of setting the signal power level at the receiver may further comprise the steps of:

(g) decreasing the signal power level at the receiver for said channel to the level below a signal detection limit of the receiver;

(h) increasing the signal power level at the receiver for said channel until it reaches the signal detection limit of the receiver;

(j) storing said signal power level at the receiver from the step (h); and

(k) calculating a operating power margin for said channel as being equal to the difference between the signal power level at the receiver in the step (e) and in the step (j), the steps (g), (h), and (j) being performed before the step (e).

In the method of the fourth embodiment of the invention, the step (c) further comprises dynamically regulating the target gain of each amplifier in the link.

The step of dynamically regulating target gain may comprise:

regulating the target gain of each amplifier so as to provide that the gain for each optical channel passing through the amplifier is within a gain ripple Δ of the amplifier, the gain ripple Δ being a variation of the amplifier gain profile with channel wavelength.

In the fifth embodiment of the invention, the method further comprises the step of adjusting the signal power levels at the transmitters in the link so as to provide that the variation in power for different channels transmitted through the link is opposite to the cumulative gain ripple of the amplifiers in the link, the cumulative gain ripple of the amplifiers being a variation of the amplifiers cumulative gain profile with channel wavelength.

Additionally, the step (a) of determining the span loss may comprise determining the span loss of each fiber span in the link remotely.

The step of remotely determining the span loss may
5 comprise:

(i) selecting a channel on the optical link and turning on the channel power at the corresponding transmitter;

(ii) increasing the power at said transmitter
10 until the signal power level at the amplifier nearest to said transmitter reaches a predetermined power level;

(iii) varying a target gain of said amplifier until the signal power level at the network element nearest to the amplifier reaches said predetermined power level;

15 (iv) repeating the step (iii) until the signal power level at all network elements on the optical link reaches the same said predetermined power level;

(v) determining the span loss of each fiber span as being equal to the following value:

20 the difference between the power at the transmitter in the step (ii) and said predetermined power level, if the fiber span is located between said transmitter and the optical amplifier nearest to the transmitter; and
the target gain of the amplifier immediately
25 preceding the fiber span, the target gain being set in the step (iii), if the fiber span is any of the remaining spans of fiber.

The step (ii) of increasing the power at said transmitter may comprise decreasing the attenuation of an
30 attenuator at said transmitter.

Additionally, the step (ii) of increasing the power at said transmitter may comprise increasing the power until the signal power level at the amplifier nearest to said transmitter reaches the predetermined power level
5 defined as the minimum specified input power of the amplifier or the average specified input power of the amplifier.

In a modification to the embodiments of the invention, the step of remotely determining the span loss
10 comprises:

determining a signal power level at an input of a fiber span in the optical link;

determining a signal power level at an output of the fiber span in the optical link; and

15 determining the loss for the fiber span to be equal to the difference between said signal power level at the input of the fiber span and said signal power level at the output of the fiber span.

According to another aspect of the invention,
20 there is provided a method for automatic initialization of an optical network having a plurality of optical links, comprising the steps of:

(l) selecting an optical link;

(m) initializing said link according to the method
25 of claim 1; and

(n) repeating the steps (l) to (m) until all links from the plurality of links in the network are initialized.

The step (l) of selecting an optical link may comprise selecting the optical link so as to optimize the
30 initialization of the optical network. Additionally, the step of selecting the optical link may comprise selecting

the optical link having the highest number of fiber spans among the remaining links to be initialized in the network.

In the method of the fourth embodiment the step (c) further comprises dynamically regulating the target gain
5 of each amplifier in the link.

The step of dynamically regulating target gain may comprise:

regulating the target gain of each amplifier so as to provide that the gain for each optical channel passing
10 through the amplifier is within a gain ripple Δ of the amplifier, the gain ripple Δ being a variation of the amplifier gain profile with channel wavelength.

In the method of the fifth embodiment the step (m) of initializing the link further comprises the step of
15 adjusting the signal power levels at the transmitters in the link so as to provide that the variation in power for different channels transmitted through the link is opposite to the cumulative gain ripple of the amplifiers in the link, the cumulative gain ripple of the amplifiers being a
20 variation of the amplifiers cumulative gain profile with channel wavelength.

Additionally, the step (a) of determining the span loss may comprise determining the span loss of each fiber span in the link remotely.

25 The step of remotely determining the span loss may comprise:

(i) selecting a channel on the optical link and turning on the channel power at the corresponding transmitter;

(ii) increasing the power at said transmitter until the signal power level at the amplifier nearest to said transmitter reaches a predetermined power level;

(iii) varying a target gain of said amplifier
5 until the signal power level at the network element nearest to the amplifier reaches said predetermined power level;

(iv) repeating the step (c) until the signal power level at all network elements on the optical link reaches the same said predetermined power level;

10 (v) determining the span loss of each fiber span as being equal to the following value:

the difference between the power at the transmitter in the step (ii) and said predetermined power level, if the fiber span is located between said transmitter
15 and the optical amplifier nearest to the transmitter; and
the target gain of the amplifier immediately preceding the fiber span, the target gain being set in the step (iii), if the fiber span is any of the remaining spans of fiber.

20 In yet another modification to the embodiments of the invention, the step of remotely determining the span loss comprises:

determining a signal power level at an input of a fiber span in the optical link;

25 determining a signal power level at an output of the fiber span in the optical link; and

determining the loss for the fiber span to be equal to the difference between said signal power level at the input of the fiber span and said signal power level at
30 the output of the fiber span.

According to yet another aspect of the invention, there is provided a method for automatic and remote

determining of a span loss of fiber spans in an optical network, comprising the steps of:

(i) selecting a channel on the optical link and turning on the channel power at the corresponding transmitter;

(ii) increasing the power at said transmitter until the signal power level at the amplifier nearest to said transmitter reaches a predetermined power level;

(iii) varying a target gain of said amplifier until the signal power level at the network element nearest to the amplifier reaches said predetermined power level;

(iv) repeating the step (iii) until the signal power level at all network elements on the optical link reaches the same said predetermined power level;

(v) determining the span loss of each fiber span as being equal to the following value:

the difference between the power at the transmitter in the step (ii) and said predetermined power level, if the fiber span is located between said transmitter and the optical amplifier nearest to the transmitter; and the target gain of the amplifier immediately preceding the fiber span, the target gain being set in the step (iii), if the fiber span is any of the remaining spans of fiber.

The step of selecting the channel may comprise selecting the channel having the highest loss on the line or having the lowest loss on the line.

According to another aspect of the invention, a system for automatic multi-level power management in an optical network comprises:

(a) means for providing a multi-level control of the amplifier, including:

(i) means for automatically determining span losses;

(ii) means for setting a target gain of the amplifier to be equal to a span loss of the fiber span immediately following the amplifier;

(iii) means for regulating the amplifier gain so as to be equal to said target gain;

(iv) means for dynamically changing said target gain of the amplifier so as to ensure that gain of a channel passing through the amplifier is within a predetermined gain range; and

(b) means for changing power of one or more channels passing through the amplifier so as to provide that power variation for the channels passing through the amplifier is within a predetermined power range.

The means (iv) for dynamically changing the target gain of the amplifier may comprise means for changing the target gain of the amplifier so as to provide that the gain of a channel passing through the amplifier is within the predetermined gain range defined as the gain ripple of the amplifier, the gain ripple being a variation of the amplifier gain profile with channel wavelength.

Additionally, the means (b) for changing the power may further comprise means for changing the power of one or more channels passing through the amplifier so as to provide that the power variation for the channels passing through the amplifier is opposite to the cumulative gain ripple of the amplifiers in the link so as to compensate for the cumulative gain ripple, the cumulative gain ripple of the amplifiers being a variation of the amplifiers cumulative gain profile with channel wavelength.

In a modification to the embodiments of the invention, the system for automatic multi-level power management in an optical network comprises means for providing a multi-level control of the amplifier, including:

5 (i) means for automatically determining span losses;

(ii) means for setting a target gain of the amplifier to be equal to a span loss of the fiber span immediately following the amplifier;

10 (iii) means for regulating the amplifier gain so as to be equal to said target gain; and

(iv) means for dynamically changing said target gain of the amplifier so as to ensure that gain of a channel passing through the amplifier is within a predetermined gain
15 range.

The means (iv) for dynamically changing the target gain of the amplifier may comprise means for changing the target gain of the amplifier so as to provide that the gain of a channel passing through the amplifier is within the
20 predetermined gain range defined as the gain ripple of the amplifier, the gain ripple being a variation of the amplifier gain profile with channel wavelength.

In another modification to the embodiments of the invention, the system for automatic multi-level power
25 management in an optical network comprises:

(a) means for providing a multi-level control of the amplifier, including:

(i) means for automatically determining span losses;

30 (ii) means for setting a target gain of the amplifier to be equal to a span loss of the fiber span immediately following the amplifier;

(iii) means for regulating the amplifier gain so as to be equal to said target gain; and

(b) means for changing power of one or more channels passing through the amplifier so as to provide that power variation for the channels passing through the amplifier is within a predetermined power range.

The means (b) for changing the power may further comprise means for changing the power of one or more channels passing through the amplifier so as to provide that the power variation for the channels passing through the amplifier is opposite to the cumulative gain ripple of the amplifiers in the link so as to compensate for the cumulative gain ripple, the cumulative gain ripple of the amplifiers being a variation of the amplifiers cumulative gain profile with channel wavelength.

According to yet another aspect of the invention there is provided an apparatus for monitoring and controlling performance of an optical network, comprising:

an amplifier for amplifying a plurality of optical channels, the amplifier having an input and an output;

an input channel power monitor for monitoring an input power of an optical channel at the input of an amplifier;

an output channel power monitor for monitoring an output power of said optical channel at the output of the amplifier; and

a controller having means for receiving data from the input and output channel power monitors and means for dynamically regulating a target gain of the amplifier in response to said data so as to provide that a gain for each channel within a selected sub-set of channels out of the

plurality of channels to be amplified is within a predetermined range.

Alternatively, the means for dynamically regulating the target gain may provide that the gain for one
5 channel only out of a plurality of channels or all channels to be amplified in the amplifier is within a predetermined range. Additionally, the means for dynamically regulating the target gain may provide that the gain for each channel within a selected sub-set of channels out of a plurality of
10 channels to be amplified in the amplifier is within a gain ripple of the amplifier, the gain ripple Δ being a variation of the amplifier gain within a band of wavelengths to be amplified.

In the apparatus of the first embodiment, the
15 means for dynamically regulating the target gain comprises:

(a) means for identifying an optical channel over the band of wavelengths that carries a signal and has the lowest gain; and

(b) means for changing the target gain of the
20 amplifier so as to provide that the gain of said channel is one of the substantially equal and equal to the following value: $G_{\text{ripple min}} = G_0 - \Delta/2$, wherein G_0 is an original target gain of the amplifier.

Additionally, the apparatus may further comprise:

25 (c) means for identifying all optical channels over the band of wavelengths that carry a signal;

(d) means for calculating an average gain G_{avg} of said channels that carry a signal;

(e) means for calculating a gain difference:

$G_{diff} = G_{ripple\ min} - G_{min\ sig}$, wherein $G_{min\ sig}$ is the gain of the channel that carries a signal and has the lowest gain; and

wherein the means (b) for changing the target gain further comprises means (f) for changing the target gain of the amplifier so as to be one of the substantially equal and equal to the following value: $G_{target} = G_{avg} + G_{diff}$.

In a modification to the apparatus of the first embodiment of the invention, the means for dynamically regulating the target gain comprises:

(a) means for identifying an optical channel over the band of wavelengths that has the lowest gain;

(b) means for identifying an optical channel over the band of wavelengths that carries a signal;

(c) means for calculating a gain difference: $G_{diff} = G_{sig} - G_{min\ gain}$, wherein $G_{min\ gain}$ is the channel that has the lowest gain and G_{sig} is the channel that carries a signal identified in (b); and

(d) means for changing the target gain of the amplifier so as to provide that the gain of the channel that carries a signal is one of the substantially equal and equal to the following value: $G_{recalculated} = G_0 - \Delta/2 + G_{diff}$, wherein G_0 is an original target gain of the amplifier.

Additionally, the apparatus may further comprise:

(e) means for identifying all optical channels over the band of wavelengths that carry a signal;

(f) means for calculating an average gain G_{avg} of said channels;

(g) means for calculating a gain difference: $\tilde{G}_{diff} = G_{recalculated} - G_{sig}$; and

wherein the means (d) for changing the target gain further comprises means (h) for changing the target gain of the amplifier so as to be one of the substantially equal and equal to the following value: $G_{target} = G_{avg} + \tilde{G}_{diff}$.

5 In a second embodiment of the apparatus, the means for dynamically regulating the target gain further comprises:

means for identifying all optical channels over the band of wavelengths that carry a signal, including means
10 for determining the number of said channels $N_{populated\ channels}$ and means for determining the gains g_i for each of said channels;

means for calculating weights w_i for said channels, such that $\sum_1^{N_{ch}} w_i = 1$, wherein N_{ch} is the total
15 number of optical channels to be amplified by the amplifier; and

means for changing the target gain of the amplifier so as to be one of the substantially equal and equal to the following value:

20 $G_{weighted\ avg} = \left[\sum_{i=populated\ channels} g_i \cdot w_i \right] \frac{N_{ch}}{N_{populated\ channels}}$, wherein N_{ch} is the total number of optical channels to be amplified by the amplifier.

In a modification to the apparatus of the second embodiment of the invention, the means for dynamically
25 regulating the target gain further comprises:

means for identifying all optical channels over the band of wavelengths that carry a signal including means for determining the gains g_i for each of said channels and means for calculating weights w_i of said channels; and

means for changing the target gain of the amplifier so as to be one of the substantially equal and equal to the following weighted-average gain value:

$$\tilde{G}_{\text{weighted avg}} = \left[\sum_{i=\text{signal channels}} g_i \cdot \tilde{w}_i \right] \text{ wherein } \tilde{w}_i = \frac{w_i}{\sum_{k=\text{signal channels}} w_k} \text{ such that}$$

$$5 \quad \sum_{i=\text{signal channels}} \tilde{w}_i = 1.$$

Additionally, the means for calculating weights may comprise:

means for sorting the optical channels over the band of wavelengths by ascending gain to form an ascending gain profile, which has an ascending channel order as its argument;

means for sorting the optical channels over the band of wavelengths by descending gain to form a descending gain profile, which has a descending channel order as its argument;

means for normalizing the descending gain profile such that $g_i' = \frac{g_i}{\sum g_i}$; and

means for forming a weight profile as the normalized descending gain profile in which the ascending channel order is used as its argument and for determining the weights for the channels from by the weight profile.

Additionally, the above means for calculating the weights may further comprise:

means for calculating an average w_{avg} of the weights;

means for calculating a center wavelength λ_c in the band of wavelengths;

means for multiplying the weights by the following weight-adjusting function: $f(\lambda) = c(\lambda - \lambda c) + w_{avg}$, wherein c is a negative constant for adjusting the weight distribution; and

5 means for normalizing the weights such that

$$\sum_{i=1}^{N_{ch}} w_i = 1.$$

According to one more aspect of the invention there is provided an apparatus for monitoring and controlling an optical amplifier, comprising:

10 means for determining a gain of an optical channel of the plurality of optical channels to be amplified in the amplifier;

means for selecting a sub-set of optical channels from the plurality of optical channels; and

15 a controller for dynamically regulating a target gain of the amplifier in response to the changes of the gain of said optical channel of the plurality of optical channels so as to provide that the gain for each optical channel from the selected sub-set of channels is within a predetermined
20 range.

According to yet one more aspect of the invention there is provided a controller for controlling an optical amplifier having an input and an output, comprising means for receiving data from channel power monitors at the input
25 and output of the amplifier and means for dynamically calculating a target gain value for the optical amplifier in response to changes in said data so as to provide that the gain for each channel within a selected sub-set of channels

out of a plurality of channels to be amplified in the amplifier is within a predetermined range.

According to a further aspect of the invention there is provided an apparatus for monitoring and
5 controlling an optical link, comprising:

means for determining a gain of an optical channel of the plurality of optical channels to be carried by the optical link;

10 means for selecting a sub-set of optical channels from the plurality of optical channels; and

means for dynamically regulating a target gain for the optical link in response to the changes of the gain of said optical channel of the plurality of optical channels so as to provide that the gain for each optical channel from
15 the selected sub-set of channels is within a predetermined range.

The apparatus above may be integrated into a package.

A system for automatic initialization of an
20 optical link in an optical network, comprising:

(a) means for determining a span loss of each fiber span in the link;

(b) means for setting a target gain of each amplifier in the link based on the span losses of the fiber
25 spans in the link;

(c) means for selecting an optical channel to be transmitted through the link and turning on the channel power;

(d) means for setting a signal power level at a
30 transmitter for said channel on the link so that to provide

transmittance of said channel through the link while the channel is amplified by the amplifier in the link;

(e) means for setting a signal power level at a receiver for said channel on the link so as to provide that
5 the power level at the receiver is within a predetermined range; and

(f) means for repeating the steps (c) to (e) until all channels to be transmitted through the link are selected.

10 According to one more aspect of the invention, there is provided a system for automatic initialization of an optical network having a plurality of optical links, comprising:

(l) means for selecting an optical link;

15 (m) the system for automatic initialization of the optical link as described in claim above; and

(n) means for repeating the steps (l) to (m) until all links from the plurality of links in the network are initialized.

20 The method and system for multi-level power management in an optical network of the embodiments of the invention include automatic initialization of the network and provide the following advantages. By adjusting the target gain of each amplifier to be equal to span losses of
25 fiber spans instead of the typical procedure of reducing signal power to match the span losses, Optical Signal-to-Noise Ratio (OSNR) in the network is improved. Component protection is another advantage provided by the embodiments of the invention. By setting the target gains of amplifiers
30 to be equal to the span losses of fiber spans, component protection is ensured. Finally, the layered structure of the power management in the network as described above allows

modular implementation of different functionalities of the power management.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings in which:

Fig. 1 illustrates a system for multi-level power management in an optical network according to the
10 embodiments of the invention;

Fig. 2 illustrates a sub-system providing a first level control of an optical amplifier in the system of Fig. 1;

Fig. 3 illustrates a sub-system providing a second
15 level control of an optical amplifier in the system of Fig. 1;

Figs. 4A, 4B and 4C illustrate the development of gain excursion for channel λ_1 within a band of channels λ_1 to λ_n amplified in an amplifier of the prior art having a
20 linear gain ripple as the number of channels that carry a signal increase;

Fig. 5 illustrates a dependence of gain of two individual channels versus the number of channels that carry a signal in the prior art apparatus for controlling an
25 amplifier under conditions causing maximal gain excursion for the channel;

Fig. 6 illustrates a sub-system providing a third level control of an optical amplifier, determination of span losses and pre-emphasis of channels in the system of Fig. 1;

Fig. 7 is a diagram illustrating the steps of the method for multi-level power management in the optical network performed in the system of Fig. 1;

5 Fig. 8 is an exemplary optical network used for illustrating methods for initialization of an optical network according to embodiments of the invention;

Fig. 9 is a flowchart illustrating the step 703 of automatically determining the span losses of an optical network in the method of Fig. 7 in more detail;

10 Fig. 10 illustrates a dependence of gain of two individual channels versus the number of channels that carry a signal in the apparatus for controlling an amplifier of the first embodiment under the same conditions as specified in Fig. 5;

15 Fig. 11 illustrates a dependence of gain of two individual channels versus the number of channels that carry a signal in the apparatus for controlling an amplifier according to a modification of the first embodiment and under the same conditions as specified in Fig. 5;

20 Fig. 12 illustrates a dependence of gain of two individual channels versus the number of channels that carry a signal in the apparatus for controlling an amplifier according to another modification of the first embodiment under the same conditions as specified in Fig. 5;

25 Figs. 13A-13D illustrate the steps of generating weights for each of the individual channels in the method and apparatus for controlling an amplifier according to another modification of the first embodiment of the invention;

Fig. 14 is another exemplary optical network used for illustrating a modification to the step 703 of determining the span losses in the methods according to embodiments of the invention;

5 Fig. 15 is yet another exemplary optical network used for illustrating another modification to the step 703 of determining the span losses in the methods according to embodiments of the invention;

10 Fig. 16 is a flowchart illustrating the steps of the method for initialization of an optical network according to the fifth embodiment of the invention; and

Fig. 17 is a flowchart illustrating the steps of a method for initialization of an optical network according to modifications of the fifth embodiment of the invention.

15

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

A system 10 for multi-level power management in an optical network, according to the embodiments of the invention, is illustrated with the aid of Figures 1 to 7.

20 The system 10 comprises three sub-systems: the sub-system 100 of the first level (level 1), the sub-system 200 of the second level (level 2), and the sub-system 300 of the third level (level 3), as shown in Fig. 1.

25 The sub-systems of the first, second, and third levels (100, 200, and 300 respectively) provide control of an amplifier locally, at a card level, and at a link level respectively. Additionally, the subsystem 300 also automatically determines span losses of fiber spans in the network and performs pre-emphasis on the channels in the
30 network. Thus, each sub-system performs a different aspect

of power management in the network, the details of which will be described below.

Fig. 2 illustrates the sub-system 100 providing the first level control of the optical amplifier. It includes a commercially available amplifier 104, having an input 106 and output 108 and an automatic gain control (AGC) loop. The AGC loop includes a loop controller 110, and input and output channel power monitors 112 and 114 at the input 106 and the output 108 of the amplifier respectively. The input and output monitors 112 and 114 may be detectors such as PIN photodiodes. Also, the optical amplifier 104 may be a double pumped EDFA or an amplifier with other types of rare earth doped fibers.

The sub-system 100 providing the first level control of the optical amplifier 104 operates as follows. The loop controller 110 dynamically regulates the amplifier gain so as to be equal to a target gain of the amplifier by regulating the amplifier pump current. The optical amplifier 104 thus operates in AGC mode.

Fig. 3 illustrates the sub-system 200 providing the second level control of the optical amplifier 104. It includes the sub-system 100 operating in AGC mode, the sub-system 100 having an input 208 and output 210 connected via a gain excursion minimization (GEM) loop 211. The GEM loop includes a GEM firmware unit 204, and input and output channel power monitors 216 and 218 at the input 208 and the output 210 of the amplifier subsystem 100 respectively.

The definition of gain excursion will be explained in more detail with the aid of Figs. 4A to 4C, which illustrate the development of gain excursion for channel λ_1 within a band of channels λ_1 to λ_n amplified in the amplifier

100 of the prior art as the number of channels that carry a signal increase. For simplicity, the amplifier 104 is chosen to have a linear gain ripple dependency 42 with a maximum gain ripple Δ designated by reference numeral 41 in
5 Figs. 4A to 4C. In Fig. 4A, the low boundary of the gain ripple 41 is represented by a solid line designated by the reference numeral 49, and the high boundary of the gain ripple 41 is represented by a solid line designated by reference numeral 47.

10 Initially, when only the lowest gain channel λ_1 carries a signal, the average gain G_{avg} and the channel gain G_1 of the channel λ_1 are set equal by the AGC to the target gain G_0 40 of the amplifier as shown in Fig. 4A. As a second channel starts to carry a signal (e.g. channel λ_n as
15 shown in Fig. 4B), in order to maintain the average gain G_{avg} of the channels that carry a signal at the same target gain G_0 of the amplifier, the gain G_1 of the channel λ_1 has to be decreased. In this particular example it is decreased by $\Delta/2$ 44, wherein Δ is the maximum gain ripple of the amplifier.
20 As more channels at the higher gain end of the spectrum 46 start to carry a signal as shown in Fig. 4C, the average gain G_{avg} increases, and the AGC of the amplifier will adjust pump laser power until the average gain G_{avg} for all channels that carry a signal and the target gain G_0 of the amplifier
25 coincide again. This will result in further decrease of the gain of the channel λ_1 , which may eventually fall beyond the gain ripple Δ , the effect being referred to as gain excursion 48 for the channel λ_1 . The value of gain excursion for a channel λ_i is measured as the difference between the
30 low boundary 49 of gain ripple (i.e. $G_0 - \Delta/2$) and the gain G_i of the channel λ_i , which is $G_0 - \Delta/2 - G_i$. Thus, the value

of gain excursion 48 for the channel λ_1 in Fig. 4C is the difference between the low boundary 49 of the gain ripple (i.e. $G_0 - \Delta/2$) and the gain G_1 of the channel λ_1 , which is $G_0 - \Delta/2 - G_1$.

5 Fig. 5 further illustrates the effect of gain excursion. In Fig. 5 is shown a dependence of gain of two individual channels versus the number of channels N that carry a signal in the prior art apparatus for controlling an amplifier under conditions causing maximal gain excursion
 10 for the channel. In the example of Fig. 5, the prior art apparatus carries 32 channels ($n=32$), and has an amplifier target gain G_0 of 22 dB and a linear amplifier gain ripple of ± 1 dB as depicted in Fig. 4. Maximal gain excursion occurs for the highest gain channel λ_{32} and the for lowest
 15 gain λ_1 channel under the following conditions: channel 32 λ_{32} 50 experiences the maximal gain excursion 54 above +1 dB ripple when it is the first channel to carry a signal and the order in which other channels start to carry a signal is from the lowest gain λ_1 up to the highest gain λ_{32} . Channel
 20 1 (λ_1) 52 experiences the maximal gain excursion 56 below -1 dB ripple when it is the first channel to carry a signal and the order in which other channels start to carry a signal is from the highest gain λ_{32} down to the lowest gain λ_2 . Thus, Fig. 5 is a plot illustrating a maximal gain excursion, and
 25 plots illustrating gains of all other channels and other orders in which channels start to carry signals will not exceed these two maximal gain excursion curves 50 and 52.

So, the cause of gain excursion is the action of the AGC of the amplifier 104 to maintain constant arithmetic
 30 average gain without accounting for the distribution of the

channels that carry a signal across a non-constant amplifier spectral gain profile.

The sub-system 200 providing the second level control of the optical amplifier operates as follows. The
5 GEM loop 211 uses the measurements of the input and input channel powers from the input and output channel power monitors 216 and 218 respectively to determine channel gains as the ratio of the output and input channel powers. The GEM loop 211 then dynamically supplies the automatic gain
10 controlled amplifier 100 with a target gain value calculated by the GEM firmware unit 204 so as to minimize or eliminate channel gain excursion and according to the methods of the embodiments of the invention as will be described in detail below.

15 Fig. 6 illustrates the sub-system 300 providing the third level control of the optical amplifier, automatic determination of span losses, and pre-emphasis of channels. It includes a number of second level sub-systems 200, linked together by spans of fiber 304 and managed by a network
20 management system (NMS) 302.

The sub-system 300 providing the third level control of the optical amplifier operates as follows. The NMS 302 automatically determines span losses of fiber spans in the network and then sets the target gain of the
25 amplifier to be equal to the span loss of the fiber span immediately following the amplifier. The NMS 302 also performs pre-emphasis on the channels in the optical network in such a manner that channel powers at the transmitters 306 are biased to compensate for the effects of optical
30 amplifier gain ripple.

Thus, a system for multi-level power management in an optical network is provided including three subsystems 100, 200, and 300 for local, card level, and link level control respectively of an amplifier in the network, as well
5 as automatic determination of span losses and pre-emphasis of channels in the network.

Fig. 7 is a diagram 700 illustrating the steps of the method for multi-level power management in the optical network performed in the system of Fig. 1 according to the
10 first embodiment of the invention. On the third level of the power management, the steps 703 to 705 of the method for multi-level power management are the automatic determination of span loss (step 703), the setting of target gain based on span loss (step 704), and the application of pre-emphasis
15 over the channels in the network (step 705), an optical link being a path of a signal from a transmitter to a receiver.

An exemplary optical network 800, implemented in the form of one optical link connecting node "A" 850 to node "B" 860, used for illustrating a method of determining span
20 loss (step 703) according to embodiments of the invention, is shown in Fig. 8. Node "A" 850 comprises a number of transmitters 802 with optical attenuators 804 at their outputs, transmitting signals that are combined by a multiplexer 806. Node "B" 860 comprises corresponding
25 receivers 810 with optical attenuators 804 at their inputs, and a demultiplexer 808 separating the combined signal received from Node "A" 850. The optical link is composed of a chain of optical amplifiers 100 having automatic gain control (AGC) linked by spans of fiber 304.

30 The network management system (NMS) 302 is connected to each of the optical amplifiers 100 and other

network elements, such as optical attenuators 806, channel power monitors 216 and 218, transmitters 802 and receivers 810. The connections are either direct or indirect and are represented by dashed lines in Fig. 8.

5 The optical network 800 in Fig. 8 also has the second level feedback control loop employed on each optical amplifier 100 comprising input and output channel power monitors, 216 and 218, located at the input and output of each optical amplifier 100, and a GEM firmware unit 204
10 connected to the optical amplifier 100 and the channel power monitors 216 and 218. The connections are represented by dotted lines in Fig. 8.

As is known in the art, optical networks can include an arbitrary number of optical amplifiers 100,
15 transmitters 802, and receivers 810, the transmitters 802 and receivers 810 being located together or at different points in the optical network from one another. Also, the second level feedback control loop mentioned above may be an optional component. Accordingly, Fig. 8 serves merely to
20 illustrate one form of optical network for the purpose of describing the embodiments of the invention.

Fig. 9 is a flowchart 900 illustrating the step 703 of automatically determining the span losses of an optical network 800 in the method of Fig. 7 in more detail.

25 Upon start 901, the procedure 900 performed by the NMS 302 selects a channel on the optical link and turns on channel power at the corresponding transmitter (step 902).

In the step 904 of Fig. 9, the procedure 900 performed by the NMS 302 increases the power at the
30 transmitter until the power level at the nearest optical

amplifier achieves a predetermined power level. The predetermined power level may be, for example, the minimum specified input power of the optical amplifier or the average specified input power of the optical amplifier. The
5 predetermined power level is achieved by, for example, decreasing the attenuation of the attenuator, such as a variable optical attenuator (VOA), located at the output of the transmitter.

In the step 906 of Fig. 9, the procedure 900
10 performed by the NMS 302 varies the amplification of the optical amplifier identified in the previous step until the signal power level at the network element nearest to the amplifier, e.g., either another optical amplifier or a receiver, achieves the same predetermined power level.

15 In the step 908 of Fig. 9, the procedure 900 performed by the NMS 302 checks whether the next network element is a receiver, signifying the end of the optical link. If the next network element is not a receiver, then the step 906 is repeated until the signal power levels at
20 all network elements on the optical link reach the same predetermined power level.

If the next network element is a receiver 810, the procedure 900 performed by the NMS 302 proceeds to the step 910.

25 In the step 910 of Fig. 9, the procedure 900 performed by the NMS 302 determines span losses for each fiber span 304. The span loss L_0 of the fiber span located between the transmitter and the optical amplifier nearest to the transmitter is the difference between the power at the
30 transmitter, as measured by a channel power monitor at the transmitter, and the predetermined power level mentioned

above. The span loss of any of the remaining fiber spans in the link is determined to be equal to the target gain of the amplifier 100 immediately preceding the fiber span 304. With the determination of the span losses for each fiber span in the link, the procedure 900 is finished (step 999).

The procedure may be performed twice with the selected channels being, for example, the channel with the highest loss and then the channel with the lowest loss. This would provide minimum and maximum span losses for each fiber span.

As mentioned above, after the span losses have been determined (step 703) the target gain of each amplifier is then set to be equal to the span loss of the fiber span immediately following the amplifier (step 704).

The application of pre-emphasis (step 705) on the channels in the network involves biasing channel powers at the transmitters to compensate or substantially compensate for the effects of optical amplifier gain ripple, which is a variation of the amplifier gain profile with channel wavelength. This is accomplished by changing the power of one or more channels passing through the amplifier so as to provide that the power variation for the channels passing through the amplifier is minimized or is within a predetermined power range.

On the second level of the power management, the step 702 of the method for multi-level power management performs minimization of gain excursion for individual channels for each amplifier in the network. Gain excursion is defined as a deviation of the gain of a channel passing through the amplifier beyond specified gain ripple of the amplifier, the deviation being caused by uneven distribution

of channels passing through the amplifier. Gain excursion minimization (GEM) involves the measurement of the input and output channel powers from the input and output channel power monitors 216 and 218 to determine channel gains as the ratio of the output to input channel powers. The GEM loop 211 dynamically supplies the automatic gain controlled amplifier 100 with a target gain value calculated by the GEM firmware unit 204 according to the methods of the embodiments of the invention as will be described in detail below.

On the first level of local control of the power management, the step 701 of the method for multi-level power management is the AGC of the optical amplifiers 104. Variations in amplifier gain are compensated by adjusting pump laser power to maintain a constant average gain through all channels that carry a signal.

The described system and method for multi-level power management in an optical network have the following advantages. By adjusting the target gain of each amplifier to be equal to span losses of fiber spans instead of the typical procedure of reducing signal power to meet a pre-determined input power level at the amplifier, OSNR in the network is improved. The physical reason behind this is as follows. Amplified Stimulated Emission (ASE) noise degrades the OSNR of an optical signal every time the signal passes through an optical amplifier, and the magnitude of the OSNR degradation depends primarily on the input power to the amplifier.

Component protection is another advantage provided by the embodiment of the invention. By setting the target gains of amplifiers to be equal to the span losses of fiber

spans, component protection is ensured. It may be especially important when span losses in the deployed network are higher than specified losses from the network planning stage, given rise to risks of component damage or
 5 amplifier saturation.

Additionally, the layered structure of the power management in the network as described above allows modular implementation of different functionalities of the power management. For example, improvement of OSNR is facilitated
 10 by the third level step 704 of setting the target gain based on span loss while dynamic network provisioning is facilitated by the second level step 702 of minimization of gain excursion for individual channels for each amplifier in the network.

Thus, the present invention provides a system and method for multi-level optical power management including AGC of amplifiers, gain excursion minimization, and pre-emphasis of channels in the optical network. The embodiment of the invention also provides a system for power management
 15 in the network that is modular, prevents component damage due to excessive power, and improves OSNR.

According to the first embodiment of the invention, step 702 of minimizing gain excursion comprises calculating the target gain to control an amplifier as
 25 illustrated in Fig. 10. The controlling of the amplifier is performed so that the gain of the lowest gain channel that carries a signal is monitored by the channel power monitors 216 and 218 and maintained at a constant value:

$G_{\text{ripple min}} = G_0 - \frac{\Delta}{2}$ where G_0 is the original amplifier target
 30 gain and Δ is the maximum amplifier gain ripple. The gain of the channel is maintained at the constant value $G_{\text{ripple min}}$

either by adjusting the amplifier target gain G_0 through the feedback control loop 211 until the gain of the channel is correct, or by calculating and applying the exact amplifier target gain G_0 that would result in the correct channel gain. The latter is accomplished by identifying all optical channels over the band of wavelengths that carry a signal, calculating an average gain G_{avg} of said channels that carry a signal, calculating a gain difference G_{diff} between the gain of the lowest gain channel that carries a signal, and the value $G_{ripple\ min}$, and changing the target gain of the amplifier so as to be substantially equal or equal to the following value: $G_{target} = G_{avg} + G_{diff}$.

Due to the accuracy of the AGC of the amplifier and the channel power monitors 216 and 218, there may be a discrepancy between the actual gain of the amplifier 104 and the target gain value G_0 . As well, for reasons of convenience, it is possible to define a target range rather than a target value for the target gain G_0 of the amplifier. In such cases, the gain of the amplifier is said to be substantially equal to the target gain G_0 .

This first embodiment is a simple implementation of the control of the amplifier that guarantees no gain excursion as is illustrated in Fig. 10. Fig. 10 illustrates a dependence of gain of two individual channels versus the number of channels that carry a signal in the apparatus for controlling an amplifier of the first embodiment under the same conditions as specified in Fig. 5 that cause maximal gain excursion. In Fig. 10, the gain G_1 of channel 1 λ_1 102 remains constant at $G_0 - \Delta/2$ because channel 1 is the lowest gain channel that will ever carry a signal. The gain G_{32} of channel 32 λ_{32} 101 does not remain constant. When only the channel 32 λ_{32} 101 carries a signal, the gain G_{32} of the

channel 32 λ_{32} 101 is $G_0 - \Delta/2$. When the lowest gain channel 1 λ_1 starts to carry a signal, the gain G_1 of the channel 1 is also $G_0 - \Delta/2$, and the gain G_{32} of the channel 32 λ_{32} increases to $G_0 + \Delta/2$. Thus, comparing Fig. 10 with Fig. 5,
 5 it is seen that gain excursion 54 and 56 are eliminated.

In a modification to the method of the first embodiment, illustrated in Fig. 11, the second level control of the amplifier is performed so that the gain of the lowest gain channel is monitored by the channel power monitors 216
 10 and 218 and maintained at a constant value: $G_{\text{ripple min}} = G_0 - \frac{\Delta}{2}$ where G_0 is the original amplifier target gain, and Δ is the maximum amplifier gain ripple.

This implementation also guarantees no gain excursion, and in addition it guarantees constant channel
 15 gain for all channels as is illustrated in Fig. 11 and will be explained below. It does however require re-calculation, based on the amplifier spectral gain profile, of the target gain for a channel that carries a signal because the lowest gain channel does not necessarily carry a signal and thus
 20 cannot always be monitored. Recalculation is accomplished by calculating a gain difference G_{diff} between the channel that has the lowest gain and the channel that carries a signal, and changing the target gain of the amplifier so as to provide that the gain of the channel that carries a
 25 signal is substantially equal or equal to the following value: $G_{\text{recalculated}} = G_0 - \Delta/2 + G_{\text{diff}}$, where G_0 is an original target gain of the amplifier, and Δ is the gain ripple. Recalculating the channel gain is not necessary if the lowest gain channel does carry a signal and thus can be
 30 monitored. Providing that the gain of the channel that carries a signal is substantially equal or equal to

$G_{recalculated}$ is accomplished by identifying all optical channels over the band of wavelengths that carry a signal, calculating an average gain G_{avg} of said channels, calculating a gain difference $\tilde{G}_{diff}$ between the gain of the channel identified above that carries a signal, and the value $G_{recalculated}$, and changing the target gain of the amplifier so as to be substantially equal or equal to the following value: $G_{target} = G_{avg} + \tilde{G}_{diff}$.

Fig. 11 illustrates a dependence of gain of two individual channels versus the number of channels that carry a signal in the apparatus for controlling an amplifier according to the modification of the first embodiment under the same conditions as specified in Fig. 5 that cause maximal gain excursion. In Fig. 11, the gain G_1 of channel 1 (λ_1) remains constant at $G_0 - \Delta/2$ because channel 1 (λ_1) is the lowest gain channel. Channel 32 (λ_{32}) remains constant at $G_0 + \Delta/2$ because the recalculation described above of the condition that $G_1 = G_0 - \Delta/2$ results now in the condition that $G_{32} = G_0 + \Delta/2$. Comparing Fig. 11 with Fig. 5, we see that gain excursions 54 and 56 are also eliminated.

Thus a method and apparatus for controlling an optical amplifier are provided, which are simple and guarantee no channel gain excursion.

A method for second level control of an amplifier according to another modification to the method of the first embodiment is illustrated in Fig. 12 and Fig. 13. The controlling is performed so that the gain g_i of each of the channels that carry a signal is monitored by the channel power monitors 216 and 218, a weight w_i is assigned to each

of the said channels, and a weighted-average gain value $G_{weighted\ avg}$ is dynamically calculated by the GEM firmware unit 204 and supplied to the AGC amplifier 100 as a new amplifier target gain value G_0 .

5 The number of channels that carry a signal $N_{populated\ channels}$ is provided by the channel power monitors 216 and 218. The total number of channels N_{ch} and the assignment of the weight w_i of each channel are provided by the GEM firmware unit 204.

10 The procedure for calculating the weighted-average gain value $G_{weighted\ avg}$ comprises identifying all optical channels over the band of wavelengths that carry a signal, determining the number of said channels $N_{populated\ channels}$, determining the gains g_i for each of said channels,

15 normalizing the weights such that $\sum_{i=1}^{N_{ch}} w_i = 1$, and calculating the weighted-average gain as follows:

$$G_{weighted\ avg} = \left[\sum_{i=populated\ channels} g_i \cdot w_i \right] \frac{N_{ch}}{N_{populated\ channels}}$$

where g_i and w_i are the channel gain and channel weight for channel i , and N_{ch} and $N_{populated\ channels}$ are the number of total channels and the number of channels that

20 carry a signal respectively.

The weights w_i of each of the channels are selected so as to complement the original gain spectrum. A procedure for generating such weights in the apparatus for

25 controlling an amplifier of the second embodiment is illustrated in Fig. 13 and is described as follows. Initially, the amplifier has a nonlinear spectral gain profile 132 as shown in Fig. 13A, wherein the gain of the

amplifier is plotted against the channel number of each of the channels within the amplification range.

1. Sort all channels within the amplification range by ascending gain. The result is a new ascending gain spectrum (profile) with ascending channel order 134

(9,1, ... 10) as its argument shown in shown in Fig. 13B.

2. Sort all channels within the amplification range by descending gain. The result is a new descending gain spectrum (profile) 136 with monotonically decreasing normalized gain as shown in Fig. 13C and a descending channel order (10, ... 1, 9) as its argument.

3. Normalize the descending gain spectrum (profile) such that $\tilde{g}_i = \frac{g_i}{\sum g_i}$.

4. Form a weight profile 138 by taking the normalized descending gain profile 136 of Step 2 above, in which the ascending channel order (9,1, ..., 10) is used as its argument as shown in Fig. 13D and determining corresponding weights w_i for the channels from the weight profile.

Thus, the weights w_i that are assigned to the channels are in exact reversal to the amplifier gain distribution.

5. For optimum performance, adjust the relative weight distribution or the tilt of the weights w_i 138 by multiplying the weights w_i 138 from Step 4 by the following weight-adjusting function:

$$f(\lambda) = c(\lambda - \lambda_c) + w_{avg}$$

where λ_c is the centre wavelength, w_{avg} is the average weight, and "c" is a negative constant for adjusting the weight distribution. Then normalize the weights such

5 that: $\sum_{k=1}^{N_{ch}} w_k = 1.$

Fig. 12 illustrates a dependence of gain of two individual channels versus the number of channels that carry a signal in the apparatus for controlling an amplifier of the second embodiment under the same conditions as specified in Fig. 5 that cause maximal gain excursion. In Fig. 12, the gain excursion of channel 1 λ_1 122 has been eliminated and that of channel 32 λ_{32} 121 has been significantly reduced.

Thus, a method of controlling an amplifier is provided which minimizes target gain variation and channel gain excursion.

In yet another modification to the method of the first embodiment, the second level control of the amplifier is performed so that another weighted-average gain value $\tilde{G}_{weighted\ avg}$ is dynamically calculated and supplied to the AGC amplifier as a new amplifier target gain value G_0 . The weighted-average gain value $\tilde{G}_{weighted\ avg}$ is defined as follows:

$$\tilde{G}_{weighted\ avg} = \left[\sum_{i=populated\ channels} g_i \cdot \tilde{w}_i \right]$$

where g_i is the channel gain for channel i , and $\tilde{w}_i$ is defined as follows:

25

$$\tilde{w}_i = \frac{w_i}{\sum_{k=\text{populated channels}} w_k}$$

where w_i is the channel weight for channel i and the weights $\tilde{w}_i$ are normalized:

$$\sum_{i=\text{populated channels}} \tilde{w}_i = 1$$

5 It is understood that other suitable methods of generating weights w_i are also possible as long as the weights w_i are normalized and they produce a minimization or elimination of channel gain excursion.

10 It is also understood that the steps of the methods for controlling an amplifier as described above may be applied to an end-to-end link to control an optical link rather than a specific amplifier. This could reduce the required hardware as the higher level feedback control loop is applied over a series of amplifiers rather than to each
15 one. Also, the accumulated channel gain excursion over an end-to-end link is larger than for one amplifier and thus requires less precise control over its correction.

In a further modification to the above embodiments, the apparatus for second level control of the
20 amplifier may comprise means for performing the above methods, which are integrated into the internal amplifier AGC 100 rather than on a higher level feedback control loop 211. This would simplify the design of the apparatus and eliminate redundant components, such as the total power
25 monitors in the automatic gain controlled amplifiers since the channel power monitors provide all necessary measurements. Optionally, the amplifier 100, the GEM firmware unit 214 and channel monitors 216 and 218 may be

integrated into a package, with other opto-electronic components if required.

In a modification to the above embodiments, determining span loss (step 703) comprises measuring channel power at both the input and output of each optical amplifier 100 in the optical link. This comprises determining the input and output signal power level of each optical amplifier 100 using the channel power monitors 216 and 218 and calculating the difference between the signal power level at the output of each fiber span (i.e. input to an amplifier) and the signal power level at the input of each fiber span (i.e. output of preceding amplifier). This difference in input and output signal power levels is the span loss of the fiber span.

In another modification to the above embodiment, the determining of span loss (step 703) comprises retrieving previously calculated span loss from the NMS 302. Exemplary optical networks used for illustrating this modification are illustrated in Fig. 14 and in Fig. 15.

Referring to Fig. 14, an optical network 142, which is similar to the network 800 of Fig. 8, is expanded to include additional amplifiers 146 and fiber spans 148 at a source 141 and/or destination 149 position of the network. The optical link 144 (represented by a solid line), for which span losses need to be determined, includes an optical link 140 (represented by a dashed line) for which the losses are already known. Accordingly, the loss of each existing fiber span in the network 142 does not need to be recalculated as it is already stored in the NMS 302 and needs only to be retrieved. Thus only the loss of each new

fiber span 148 needs to be calculated according to the method described above.

Referring to Fig. 15, the determination of span loss is performed on one optical link at a time and it may occur that a link 154 (represented by a solid line) for which span losses need to be determined is a subset of an optical link 150 having a higher number of spans (represented by a dashed line) whose losses have already been determined. In such an instance, the span loss of each fiber span in the link 154 is already stored in the NMS 302 and needs only to be retrieved.

According to the second embodiment of the invention, the power management of the optical network includes only the first (local) and second (card level) of control as described above.

According to the third embodiment of the invention, the power management of the optical network includes only a first (local) and a third (link level) of control of an amplifier as well as automatic determination of span losses and pre-emphasis of channels in the network as described above.

According to the fourth embodiment of the invention, the power management of the optical network includes more than three levels of control. Additional levels may be, for example, a fourth level of control, in which NMSs 302 of different networks interact to provide control of amplifiers in these networks.

The exemplary optical network 800 shown in Fig. 8 is used for illustrating the step of initialization of the optical network according to the fifth embodiment of the

invention. The method of the fifth embodiment is similar to the first embodiment except for an additional step being added, namely the step of automatic initialization of the network, which is performed before all other steps.

- 5 According to the fifth embodiment of the invention, the step of automatic initialization of the network may be implemented from the steps 701 to 705 of multi-level power management.

The network 800 is initialized in the following
10 manner. The NMS 302 initializes the optical network 800 by determining fiber span losses and setting the operating points of the network components according to the methods of the embodiments of the invention as will be described in detail below.

15 The feedback control loop for the amplifier provides additional optimization of the network in the form of gain excursion minimization (GEM) by dynamically regulating the target gain of the amplifier, if additional power margin is required. Also, the NMS 302 may provide
20 pre-emphasis control of the link, in which channel powers at the transmitters are biased to compensate for the effects of optical amplifier gain ripple.

Fig. 16 is a flowchart 1600 illustrating the steps of the method for third level power management of the
25 optical network 800 according to the fifth embodiment of the invention. The power management is performed on one optical link at a time, wherein each optical link is a path of a channel from one of the transmitters 802 on Node "A" 850 to one of the corresponding receivers 810 on Node "B" 860. The
30 optical network 800 illustrated in Fig. 8 has a single optical link as was mentioned above.

Upon start 1601, the procedure 1600 performed by the NMS 302 determines the span loss of each fiber span 304 in the optical link (step 1602). Remote, automatic methods of determining the span loss was described in detail above.

5 In the step 1604 of Fig. 16, the procedure 1600 performed by the NMS 302 sets the target gain of each optical amplifier 100 and the signal power level at each transmitter 802 (Tx) and receiver 810 (Rx).

The signal power level at each transmitter 802 is
 10 set to be substantially equal to its maximum power $P_{Tx \max}$ by, for example, setting the attenuation L_{Tx} of an optical attenuator at the transmitter to about zero attenuation. However, if the loss L_0 of the fiber span located between the transmitter 802 and the nearest optical amplifier is
 15 less than the minimum span loss L_{min} specified for the network, the attenuation L_{Tx} of the optical attenuator at the transmitter is set to be substantially equal to the following value:

$$L_{Tx} = L_{min} - L_0$$

20 so that the power at the transmitter is substantially equal to $P_{Tx \max} - L_{min} + L_0$.

The target gain G_1 of the optical amplifier nearest to the transmitter is set to the following value:

$$G_1 = (P_{max} - P_{Tx}) + L_0$$

25 where P_{max} is the maximum specified power for a channel in the optical network, and P_{Tx} is the average power of the transmitters 802 in the link. The target gain G_i of each of the remaining optical amplifiers is set to

substantially compensate for the span loss L_i of the fiber span following each optical amplifier. This provides that the network operates at a desirable power level with the maximum specified power for a channel P_{max} present at the
5 output of each optical amplifier 110 in the network.

The signal power level at each receiver 810 is set to a level below the signal detection limit of the receiver. This is accomplished by, for example, setting the attenuation of an optical attenuator at the receiver to
10 maximum attenuation.

After performing the step 1604 of setting the target gain of each optical amplifier 100 and the signal power level at each transmitter 802 (Tx) and receiver 810 (Rx), the procedure 1600 performed by the NMS 302 selects
15 and turns on channel power to a channel on the optical link (step 1606).

In the step 1608 of Fig. 16, the procedure 1600 performed by the NMS 302 increases the signal power level at the receiver on the channel being optimized until the power
20 level reaches the signal detection limit of the receiver. The channel power at the receiver (Rx) is stored in the step 1610 of Fig. 16 for later use.

In the step 1612 of Fig. 16, the procedure 1600 performed by the NMS 302 increases the signal power level at
25 the receiver on the channel being optimized until it is within a predetermined range or, if this is not possible, until the maximum power is reached. The signal power level may be set to, for example, a specified power margin P_{margin} for each channel subtracted from the maximum specified
30 channel power $P_{Rx\ max}$ to the receiver.

In the step 1614 of Fig. 16, the procedure 1600 performed by the NMS 302 calculates the operating power margin of the channel as being equal to the difference between the signal power levels at the receiver in the step 5 1612 and in the step 1610. The operating power margin is monitored to protect the network, such as by guarding against receiver damage due to power overload.

In the step 1616 of Fig. 16, the procedure 1600 performed by the NMS 302 checks if there are additional 10 channels on the optical link to be initialized. If there are additional channels, then the procedure 1600 selects and turns on the channel power to the next channel to be initialized (step 1618) and the steps 1608 to 1614 are repeated. If there are no additional channels, the procedure 15 of third level power management is finished (step 1699) for the current optical link.

Thus, a method for initialization of an optical link in an optical network is provided that is simple, universal, requires limited component hardware and 20 consequently low component cost. Additionally, it tracks the operating power margin of the channels on the link in the network to monitor the health of the network. As well, the initialization method includes a method for determining the span losses of an optical link that is accurate and is 25 performed automatically. The initialization method is repeated for each optical link in the optical network.

Fig. 17 shows a flowchart 1700 illustrating the steps of the methods for initialization of an optical network according to modifications of the fifth embodiment 30 of the invention. The modifications of the fifth embodiment are similar to the fifth embodiment except for additional

steps being added, namely the step 1720 of applying gain excursion minimization (GEM) to each amplifier and the step 1722 of applying pre-emphasis to the optical link. The same steps in flowcharts 1600 and 1700 are designated by the same
5 reference numerals in Fig. 16 and Fig. 17.

According to a modification to the fifth embodiment of the invention, the step 1720 of Fig. 17 is applied after the step 1618 in which the procedure 1700 selects and turns on channel power to the next channel to be
10 initialized. In the step 1720 of Fig. 17, the procedure 1700 performed by the NMS 302 applies gain excursion minimization (GEM) to the amplifiers 100 in the link.

Thus, a method for initialization of an optical link in an optical network is provided that is additionally
15 enhanced by gain excursion minimization so that dynamic adding and dropping of multiple channels is supported.

According to another modification to the fifth embodiment of the invention, the step 1722 of Fig. 17 is added after all channels on the optical link have been
20 initialized. In the step 1722 of Fig. 17, the procedure 1700 performed by the NMS 302 determines the power variation for different channels due to cumulative gain ripple of the amplifiers in the optical link and biases channel powers at the transmitters to compensate or substantially compensate
25 for the effects of the cumulative gain ripple. This biasing of channel powers is accomplished by adjusting the signal power levels at the transmitters and/or the attenuations of attenuators at the transmitters so that the power variation at the transmitters is opposite to the cumulative gain
30 ripple of the amplifiers in the link, resulting in the power variation for the channels passing through the amplifier

being minimized or within a predetermined power range. This adjusting of signal power levels to compensate for the effects of amplifier gain ripple is referred to as pre-emphasis and it minimizes the deleterious effects of power variation on the optical link. It may be implemented by, for example, adjusting the signal power levels of the channels so that they are substantially equal in value upon reaching the middle of the optical link. The adjustment of the signal power levels of the channels is performed under the condition that the signal power levels remain within the operating power margin of the channel as calculated in the step 1614 of Fig. 16.

Thus, a method for initialization of an optical link in an optical network is provided that minimizes the effects of amplifier gain ripple.

Referring to Fig. 15, the initialization method is performed on one optical link at a time and it may occur that a link 154 (represented by a solid line) for which span losses need to be determined is a subset of an optical link 150 having a higher number of spans (represented by a dashed line) whose losses have already been determined. In such an instance, the span loss of each fiber span in the link 154 is already stored in the NMS 302 and needs only to be retrieved.

From the modifications described above, it is clear that the order in which optical links are initialized and brought to the required operating points in the optical network may be optimized well. For example, it is beneficial to initialize optical links, each having a number of fiber spans in the order of decreasing number of spans, so that the method for determining span losses on subsequent optical

links may claim benefit from the span losses already stored in the NMS 302.

It is apparent to those skilled in the art that there are many variations of the present invention that
5 retain the spirit of the invention. Thus it is intended that the present invention cover the modifications, variations, and adaptations of this invention provided they fall within the scope of the following claims.

Claims**What is claimed is:**

1. A method for monitoring and controlling an optical amplifier, comprising the steps of:
 - determining a gain of an optical channel of the plurality of optical channels to be amplified in the amplifier;
 - selecting a sub-set of optical channels from the plurality of optical channels; and
 - dynamically regulating a target gain of the amplifier in response to the changes of the gain of said optical channel of the plurality of optical channels so as to provide that the gain for each optical channel from the selected sub-set of channels is within a predetermined range;
 - wherein the step of dynamically regulating the target gain of the amplifier so as to provide that the gain for each channel from the selected sub-set of channels is within a gain ripple Δ of the amplifier, the gain ripple Δ being a variation of the amplifier gain profile within a band of wavelengths to be amplified; and
 - wherein the step of dynamically regulating the target gain of the amplifier further comprises:
 - (a) identifying an optical channel over the band of wavelengths that carries a signal and has the lowest gain; and
 - (b) changing the target gain of the amplifier so as to provide that the gain of said channel is substantially equal to the following value $G_{\text{ripple min}} = G_0 - \Delta/2$, wherein G_0 is an original target gain of the amplifier.
2. A method as described in claim 1, wherein the step (b) of changing the target gain comprises changing the target gain so as to provide that the gain of said channel is equal to $G_{\text{ripple min}}$.
3. A method as described in claim 1, further comprising:
 - (c) identifying all optical channels over the band of wavelengths that carry a signal;
 - (d) calculating an average gain G_{avg} of said channels that carry a signal;
 - (e) calculating a gain difference: $G_{\text{diff}} = G_{\text{ripple min}} - G_{\text{min sig}}$, wherein $G_{\text{min sig}}$ is the gain of the

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channel that carries a signal and has the lowest gain, the steps (c), (d), and (e) being performed before step (b); and

wherein the step (b) comprises the step of (f) changing the target gain of the amplifier so as to be substantially equal the following value: $G_{target} = G_{avg} + G_{diff}$.

4. A method as described in claim 3, wherein the step (f) of changing the target gain comprises changing the target gain so as to be equal to G_{target} .

5. A method as described in claim 1, wherein the step of dynamically regulating the target gain of the amplifier further comprises:

- (a) identifying an optical channel over the band of wavelengths that has the lowest gain;
- (b) identifying an optical channel over the band of wavelengths that carries a signal;
- (c) calculating a gain difference: $G_{diff} = G_{sig} - G_{min\ gain}$, wherein $G_{min\ gain}$ is the channel that has the lowest gain and G_{sig} is the channel that carries a signal identified in (b); and
- (d) changing the target gain of the amplifier so as to provide that the gain of the channel that carries a signal is substantially equal to the following value: $G_{recalculated} = G_0 - \Delta/2 + G_{diff}$, wherein G_0 is an original target gain of the amplifier.

6. A method as described in claim 5, wherein the step (d) of changing the target gain comprises changing the target gain so as to provide that the gain of said channel is equal to $G_{recalculated}$.

7. A method as described in claim 5, further comprising:

- (e) identifying all optical channels over the band of wavelengths that carry a signal;
- (f) calculating an average gain G_{avg} of said channels;
- (g) calculating a gain difference $\tilde{G}_{diff} = G_{recalculated} - G_{sig}$, the steps (e), (f), and (g) being performed before step (d); and

wherein the step (d) comprises the step of (h) changing the target gain of the amplifier so as to be substantially equal to the following value:

$$G_{target} = G_{avg} + \tilde{G}_{diff} .$$

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8. A method as described in claim 7, wherein the step (h) of changing the target gain comprises changing the target gain so as to be equal to G_{target} .

9. A method as described in claim 1, wherein the step of dynamically regulating the target gain of the amplifier further comprises:

identifying all optical channels over the band of wavelengths that carry a signal, including determining the number of said channels $N_{populated\ channels}$ and determining the gains g_i for each of said channels;

calculating weights w_i for said channels, such that $\sum_1^{N_{ch}} w_i = 1$, wherein N_{ch} is the total number of

optical channels to be amplified by the amplifier; and

changing the target gain of the amplifier so as to be substantially equal to the following value:

$$G_{weighted\ avg} = \left[\sum_{i=signal\ channels} g_i \cdot w_i \right] \frac{N_{ch}}{N_{signal\ channels}}, \text{ wherein } N_{ch} \text{ is the total number of optical channels}$$

to be amplified by the amplifier.

10. A method as described in claim 9, wherein the step of changing the target gain comprises changing the target gain so as to be equal to $G_{weighted\ average}$.

11. A method as described in claim 1, wherein the step of dynamically regulating the target gain of the amplifier further comprises:

identifying all optical channels over the band of wavelengths that carry a signal, including determining the gains g_i for each of said channels and calculating weights w_i of said channels; and changing the target gain of the amplifier so as to be substantially equal to the following

$$\text{value: } \tilde{G}_{weighted\ avg} = \left[\sum_{i=signal\ channels} g_i \cdot \tilde{w}_i \right], \text{ wherein } \tilde{w}_i = \frac{w_i}{\sum_{k=signal\ channels} w_k} \text{ such that}$$

$$\sum_{i=signal\ channels} \tilde{w}_i = 1.$$

12. A method as described in claim 11, wherein the step of changing the target gain comprises changing the target gain so as to be equal to $\tilde{G}_{weighted\ avg}$.

13. A method as described in claim 9, wherein the step of calculating the weights comprises:
 sorting the optical channels over the band of wavelengths by ascending gain to form an ascending gain profile, which has an ascending channel order as its argument;
 sorting the optical channels over the band of wavelengths by descending gain to form a descending gain profile, which has a descending channel order as its argument;
 normalizing the descending gain profile such that $g_i' = \frac{g_i}{\sum g_i}$; and
 forming a weight profile as the normalized descending gain profile in which the ascending channel order is used as its argument; and
 determining the weights for the channels from the weight profile.

14. A method as described in claim 13, further comprising:
 calculating an average w_{avg} of the weights;
 calculating a center wavelength λ_c in the band of wavelengths;
 multiplying the weights by the following weight-adjusting function:
 $f(\lambda) = c(\lambda - \lambda_c) + w_{avg}$, wherein c is a negative constant for adjusting the weight distribution;
 and

normalizing the weights such that $\sum_1^{N_{ch}} w_i = 1$.

15. A method as described in claim 11, wherein the step of calculating the weights comprises:
 sorting the optical channels over the band of wavelengths by ascending gain to form an ascending gain profile, which has an ascending channel order as its argument;
 sorting the optical channels over the band of wavelengths by descending gain to form a descending gain profile, which has a descending channel order as its argument;

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normalizing the descending gain profile such that $g_i' = \frac{g_i}{\sum g_i}$; and

forming a weight profile as the normalized descending gain profile in which the ascending channel order is used as its argument; and

determining the weights for the channels from the weight profile.

16. A method as described in claim 15, wherein the step of calculating the weights further comprises:

calculating an average w_{avg} of the weights;

calculating a center wavelength λ_c in the band of wavelengths;

multiplying the weights by the following weight-adjusting function:

$f(\lambda) = c(\lambda - \lambda_c) + w_{avg}$, wherein c is a negative constant; and

normalizing the weights such that $\sum_1^{N_{ch}} w_i = 1$.

17. An apparatus for monitoring and controlling performance of an optical network, comprising:
an amplifier for amplifying a plurality of optical channels, the amplifier having an input and an output;

an input power channel monitor for monitoring an input power of an optical channel at the input of an amplifier;

an output channel power monitor for monitoring an output power of said optical channel at the output of the amplifier; and

a controller having means for receiving data from the input and output channel power monitors and means for dynamically regulating a target gain of the amplifier in response to said data so as to provide that a gain for each channel within a selected sub-set of channels out of the plurality of channels to be amplified is within a predetermined range;

wherein the means for dynamically regulating the target gain comprises means for dynamically regulating the target gain of the amplifier so as to provide that the gain for each channel within a selected sub-set of channels out of a plurality of channels to be amplified in the amplifier is within a

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gain ripple of the amplifier, the gain ripple Δ being a variation of the amplifier gain within a band of wavelengths to be amplified; and

wherein the means for dynamically regulating the target gain comprises:

- (a) means for identifying an optical channel over the band of wavelengths that carries a signal and has the lowest gain; and
- (b) means for changing the target gain of the amplifier so as to provide that the gain of said channel is one of the substantially equal and equal to the following value: $G_{ripple\ min} = G_0 - \Delta/2$, wherein G_0 is an original target gain of the amplifier.

18. An apparatus as described in claim 17, further comprising:

- (c) means for identifying all optical channels over the band of wavelengths that carry a signal;
- (d) means for calculating an average gain G_{avg} of said channels that carry a signal;
- (e) means for calculating a gain difference:

$G_{diff} = G_{ripple\ min} - G_{min\ sig}$, wherein $G_{min\ sig}$ is the gain of the channel that carries a signal and has the lowest gain; and

wherein the means (b) for changing the target gain further comprises means (f) for changing the target gain of the amplifier so as to be one of the substantially equal and equal to the following value: $G_{target} = G_{avg} + G_{diff}$.

19. An apparatus as described in claim 17, wherein the means for dynamically regulating the target gain comprises:

- (a) means for identifying an optical channel over the band of wavelengths that has the lowest gain;
- (b) means for identifying an optical channel over the band of wavelengths that carries a signal;
- (c) means for calculating a gain difference: $G_{diff} = G_{sig} - G_{min\ gain}$, wherein $G_{min\ gain}$ is the channel that has the lowest gain and G_{sig} is the channel that carries a signal identified in (b); and
- (d) means for changing the target gain of the amplifier so as to provide that the gain of the channel that carries a signal is one of the substantially equal and equal to the following value: $G_{recalculated} = G_0 - \Delta/2 + G_{diff}$, wherein G_0 is an original target gain of the amplifier.

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20. An apparatus as described in claim 19, further comprising:

(e) means for identifying all optical channels over the band of wavelengths that carry a signal;

(f) means for calculating an average gain G_{avg} of said channels;

(g) means for calculating a gain difference: $\tilde{G}_{diff} = G_{recalculated} - G_{sig}$; and

wherein the means (d) for changing the target gain further comprises means (h) for changing the target gain of the amplifier so as to be one of the substantially equal and equal to the following value: $G_{target} = G_{avg} + \tilde{G}_{diff}$.

21. An apparatus as described in claim 17, wherein the means for dynamically regulating the target gain further comprises:

means for identifying all optical channels over the band of wavelengths that carry a signal, including means for determining the number of said channels $N_{populated\ channels}$ and means for determining the gains g_i for each of said channels;

means for calculating weights w_i for said channels, such that $\sum_1^{N_{ch}} w_i = 1$, wherein N_{ch} is the total number of optical channels to be amplified by the amplifier; and

means for changing the target gain of the amplifier so as to be one of the substantially equal and

equal to the following value: $G_{weighted\ avg} = \left[\sum_{i=populated\ channels} g_i \cdot w_i \right] \frac{N_{ch}}{N_{populated\ channels}}$, wherein N_{ch} is the total number of optical channels to be amplified by the amplifier.

22. An apparatus as described in claim 17, wherein the means for dynamically regulating the target gain further comprises:

means for identifying all optical channels over the band of wavelengths that carry a signal including means for determining the gains g_i for each of said channels and means for calculating weights w_i of said channels; and

means for changing the target gain of the amplifier so as to be one of the substantially equal and

equal to the following weighted-average gain value: $\tilde{G}_{weighted\ avg} = \left[\sum_{i=sigal\ channels} g_i \cdot \tilde{w}_i \right]$ wherein

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$$\tilde{w}_i = \frac{w_i}{\sum_{k=\text{signal channels}} w_k} \text{ such that } \sum_{i=\text{signal channels}} \tilde{w}_i = 1.$$

23. An apparatus as described in claim 21, wherein the means for calculating the weights comprises:

means for sorting the optical channels over the band of wavelengths by ascending gain to form an ascending gain profile, which has an ascending channel order as its argument;

means for sorting the optical channels over the band of wavelengths by descending gain to form a descending gain profile, which has a descending channel order as its argument;

means for normalizing the descending gain profile such that $g_i' = \frac{g_i}{\sum g_i}$; and

means for forming a weight profile as the normalized descending gain profile in which the ascending channel order is used as its argument and for determining the weights for the channels from by the weight profile.

24. An apparatus as described in claim 23, further comprising:

means for calculating an average w_{avg} of the weights;

means for calculating a center wavelength λ_c in the band of wavelengths;

means for multiplying the weights by the following weight-adjusting function: $f(\lambda) = c(\lambda - \lambda_c) + w_{avg}$, wherein c is a negative constant for adjusting the weight distribution; and

means for normalizing the weights such that $\sum_1^{N_{ch}} w_i = 1$.

25. An apparatus as described in claim 22, wherein the means for calculating the weights comprises:

means for sorting the optical channels over the band of wavelengths by ascending gain to form an ascending gain profile, which has an ascending channel order as its argument;

means for sorting the optical channels over the band of wavelengths by descending gain to form a descending gain profile, which has a descending channel order as its argument;

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means for normalizing the descending gain profile such that $g_i' = \frac{g_i}{\sum g_i}$; and

means for forming a weight profile as the normalized descending gain profile in which the ascending channel order is used as its argument and for determining the weights for the channels from by the weight profile.

26. An apparatus as described in claim 25, further comprising:

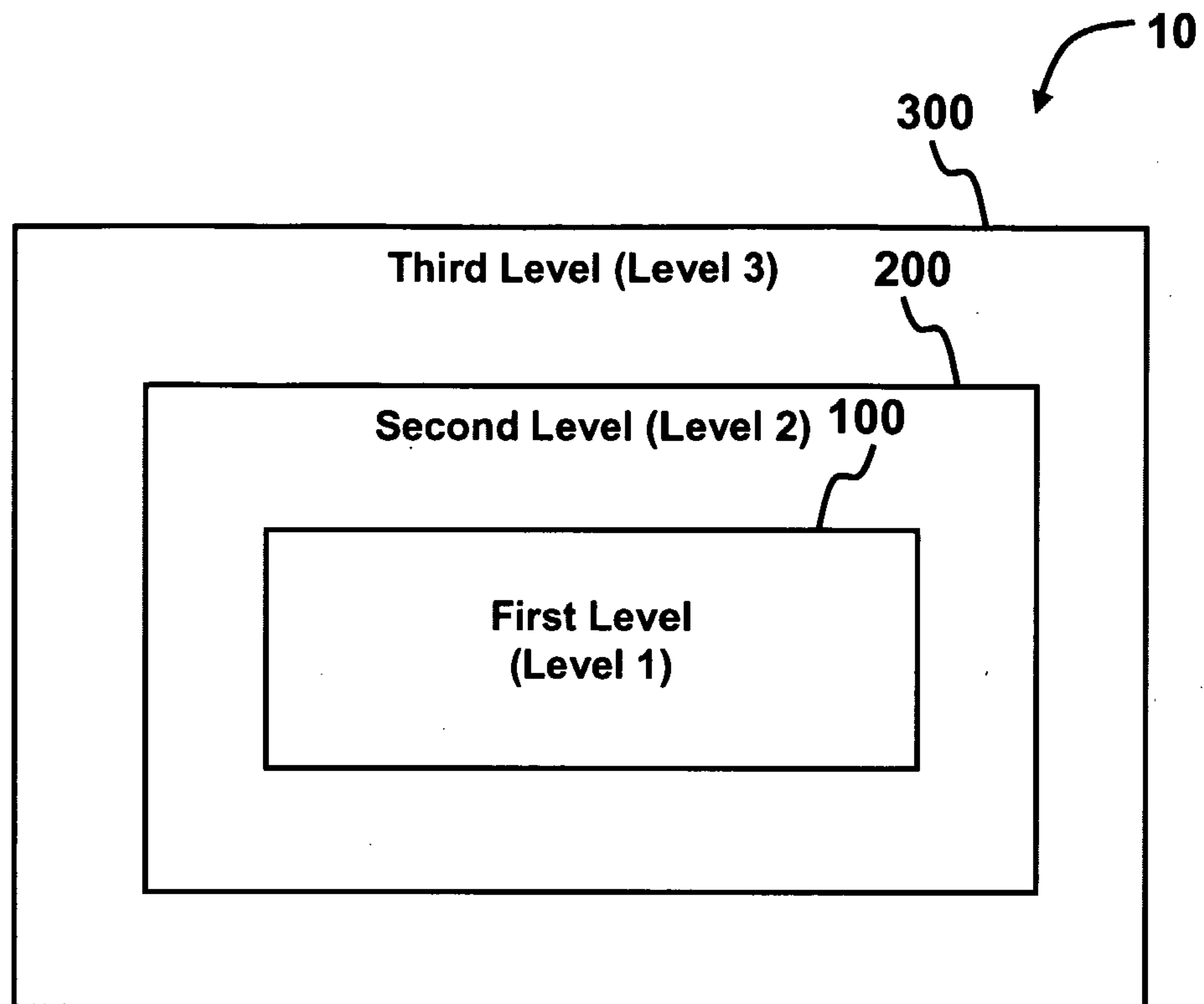
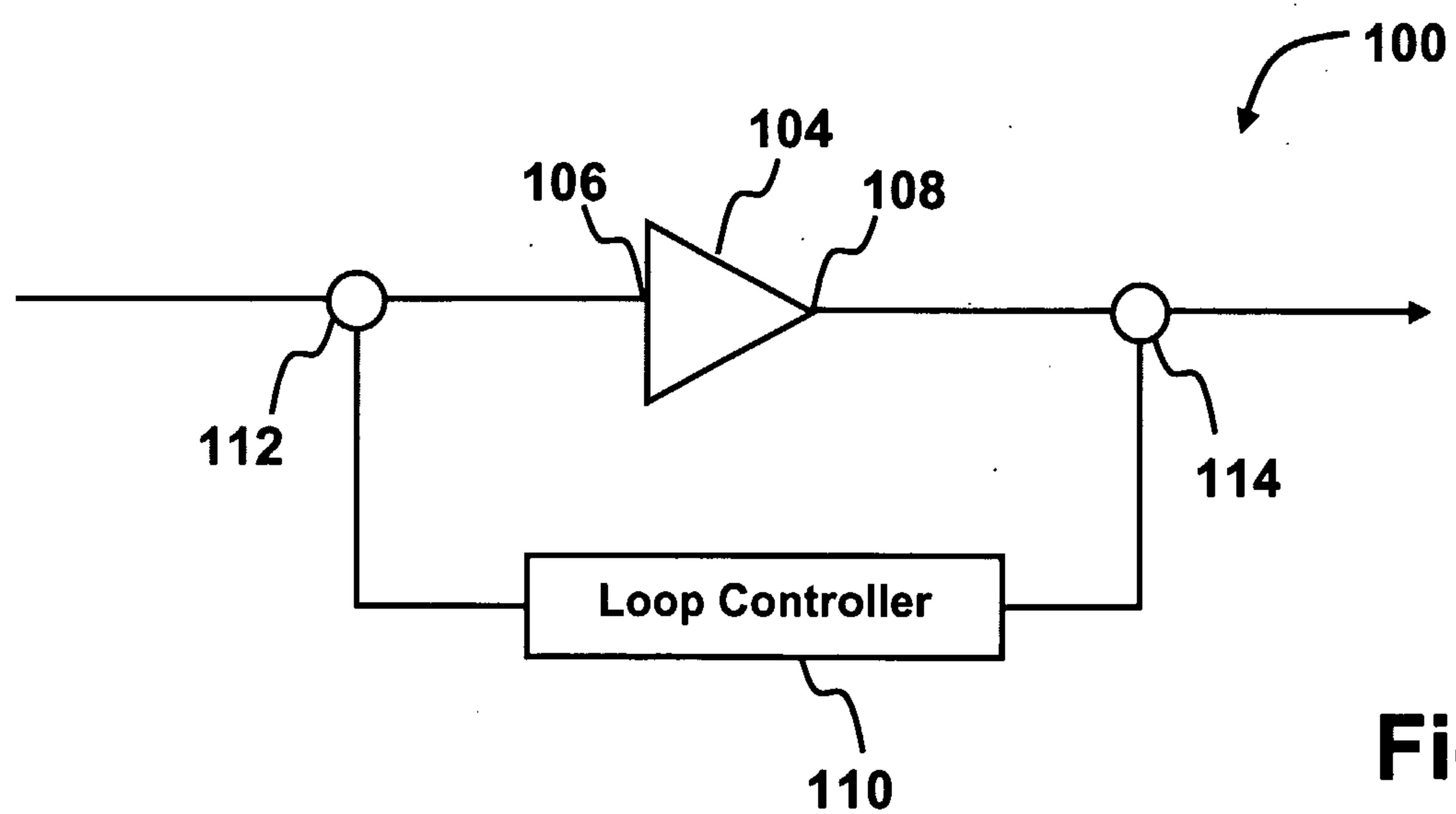
means for calculating an average w_{avg} of the weights;

means for calculating a center wavelength λ_c in the band of wavelengths;

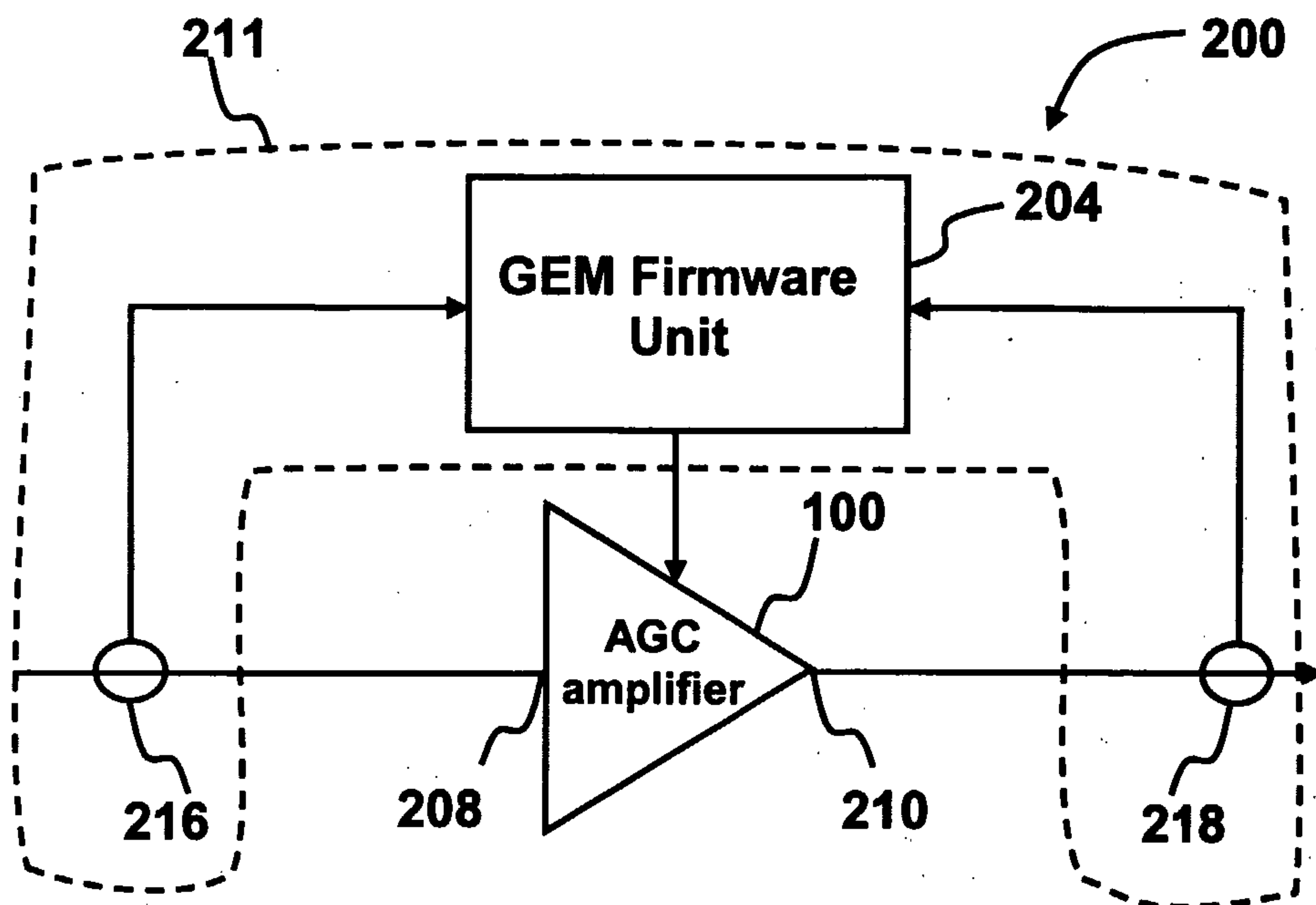
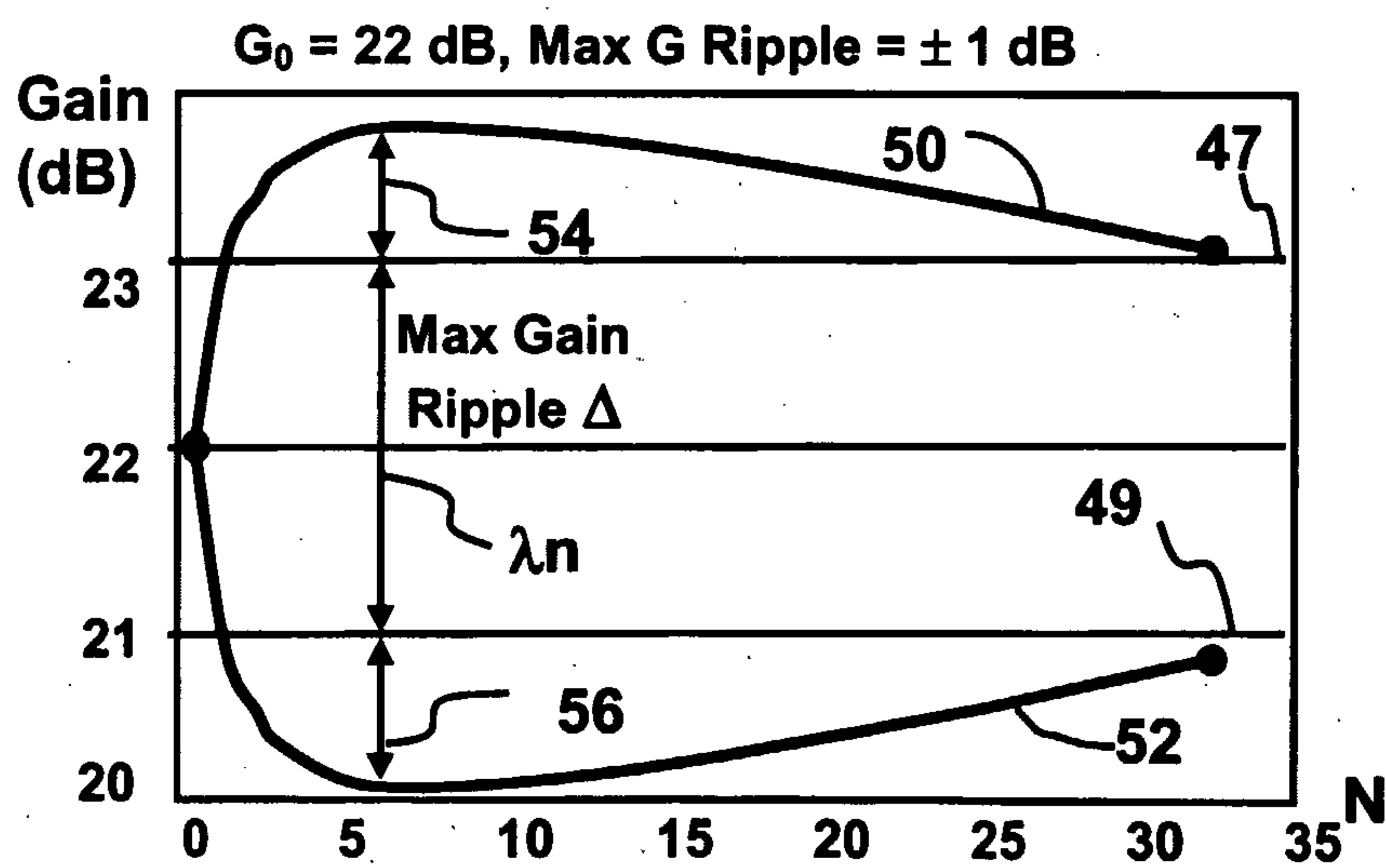
means for multiplying the weights by the following weight-adjusting function: $f(\lambda) = c(\lambda - \lambda_c) + w_{avg}$, wherein c is a negative constant for adjusting the weight distribution; and

means for normalizing the weights such that $\sum_1^{N_{ch}} w_i = 1$.

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**Fig. 1****Fig. 2**

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**Fig. 3****Fig. 5**
PRIOR ART

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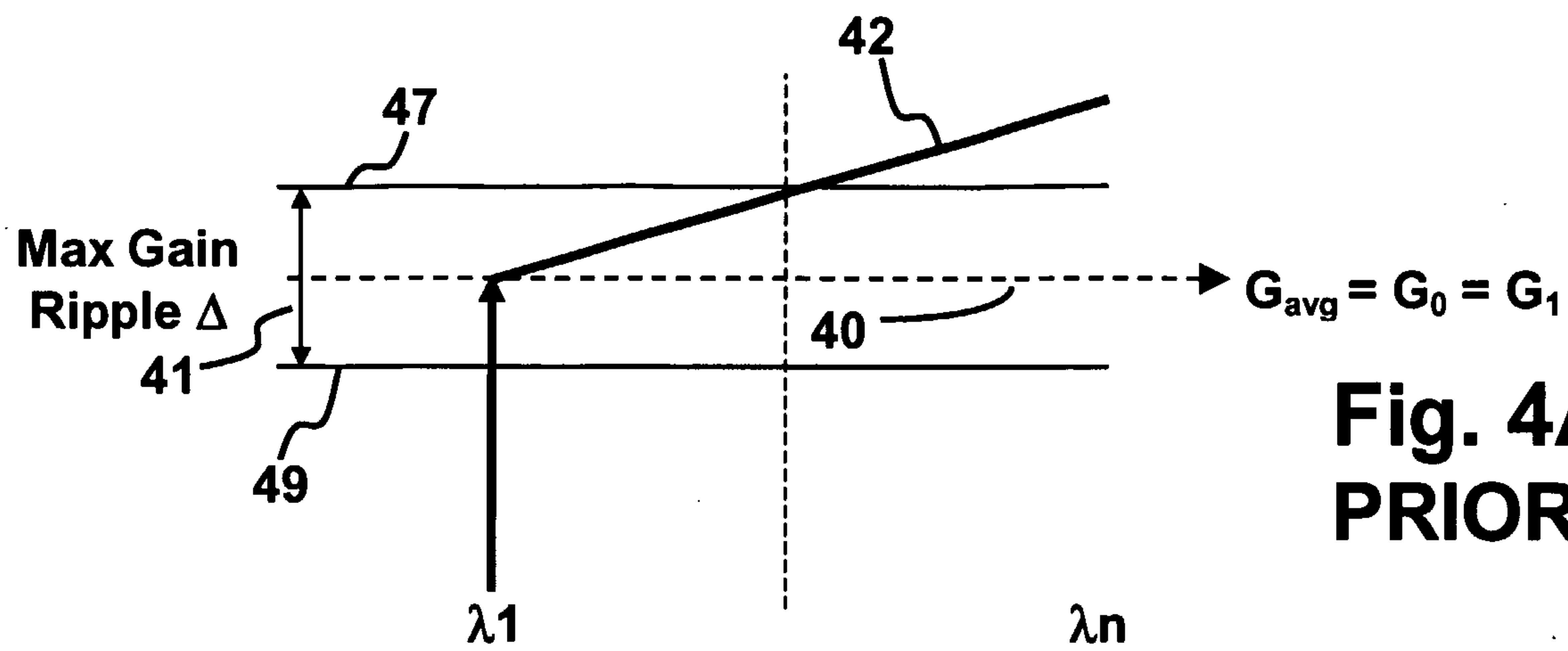


Fig. 4A
PRIOR ART

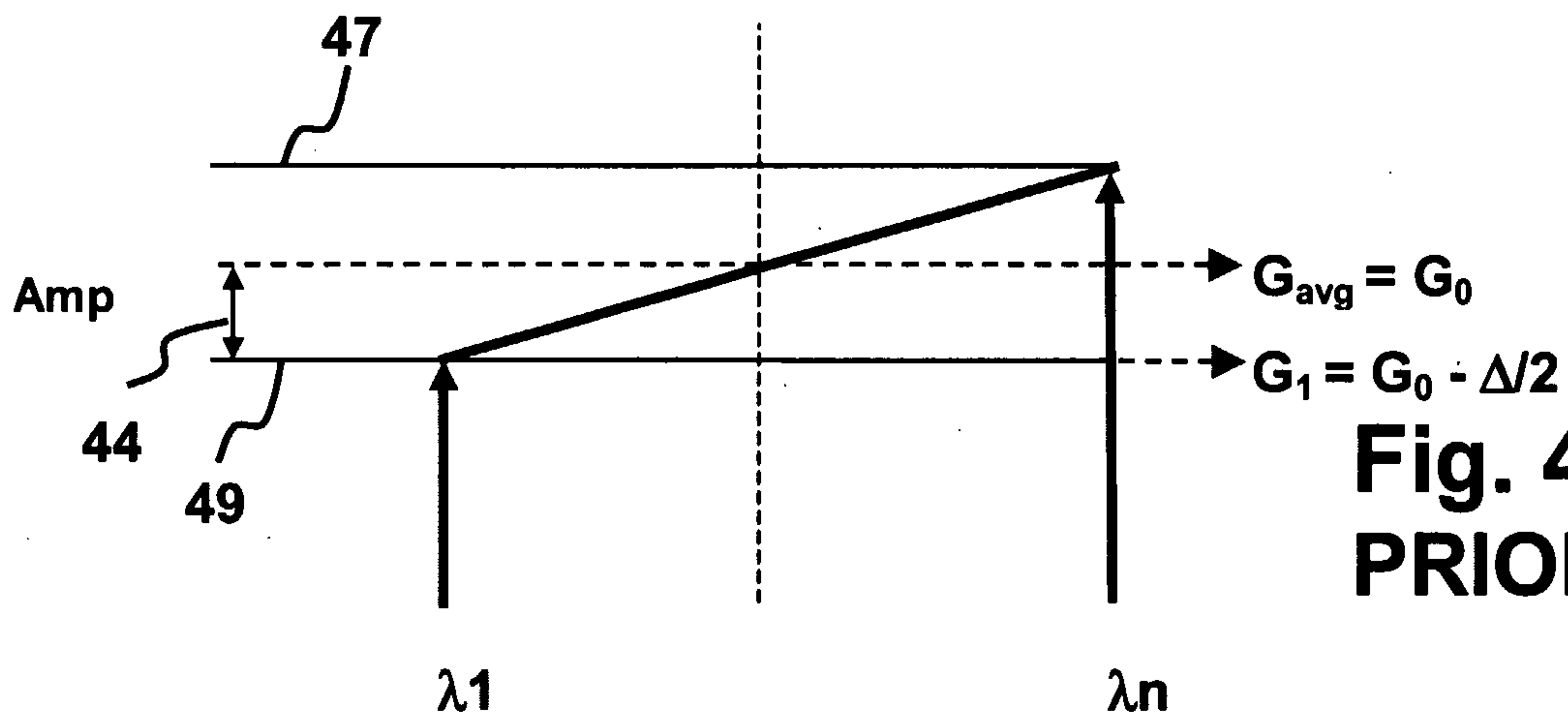


Fig. 4B
PRIOR ART

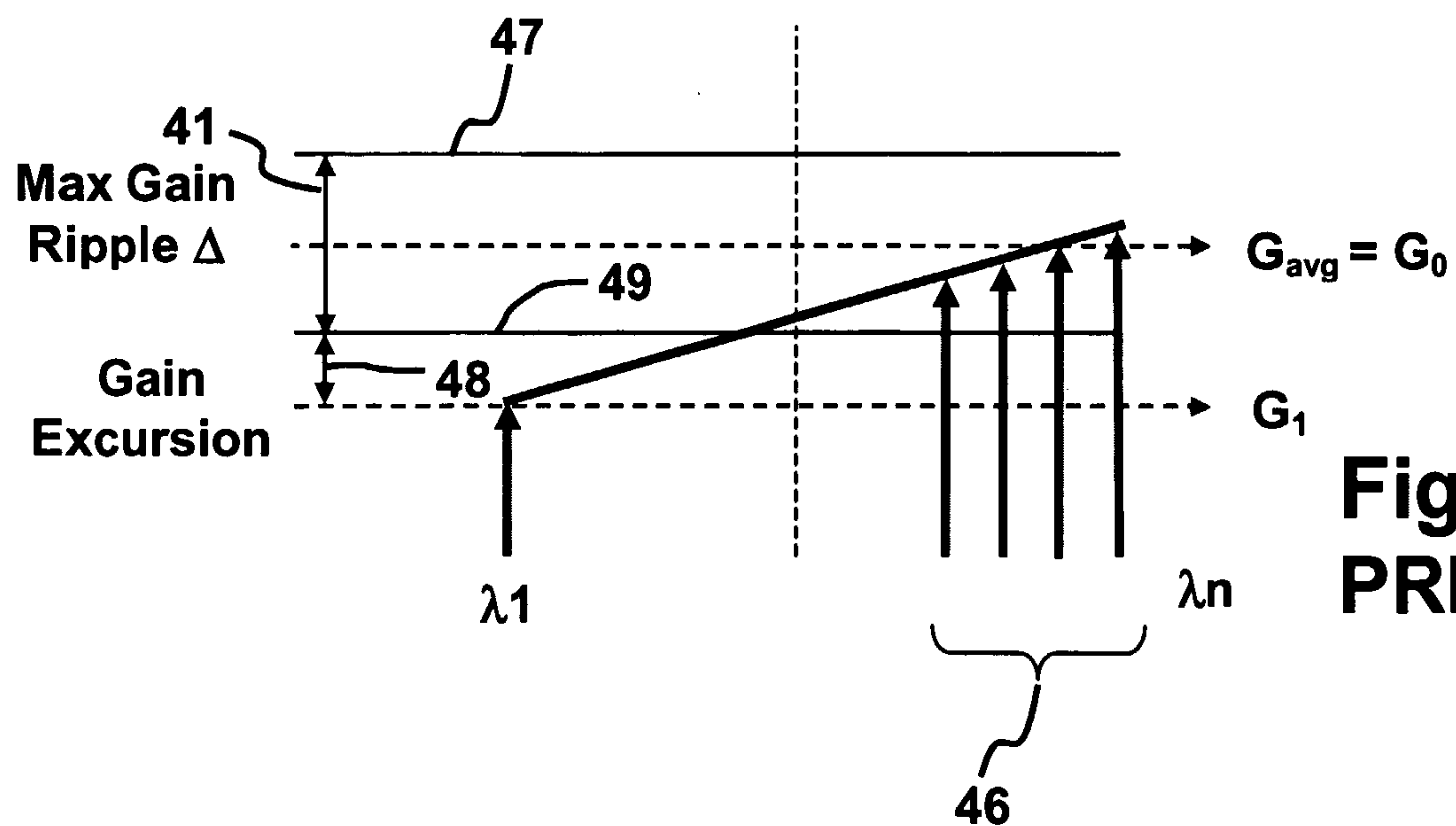


Fig. 4C
PRIOR ART

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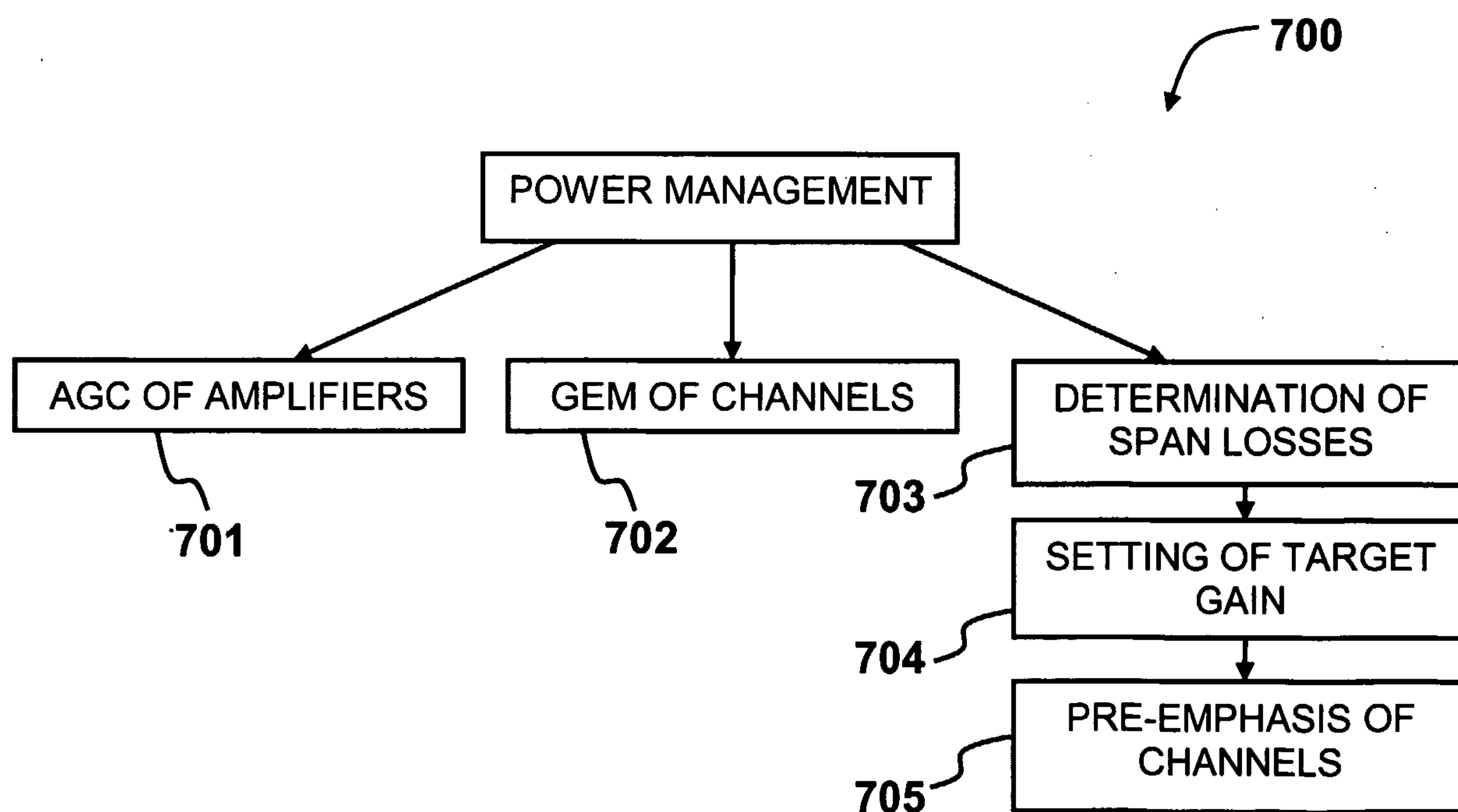
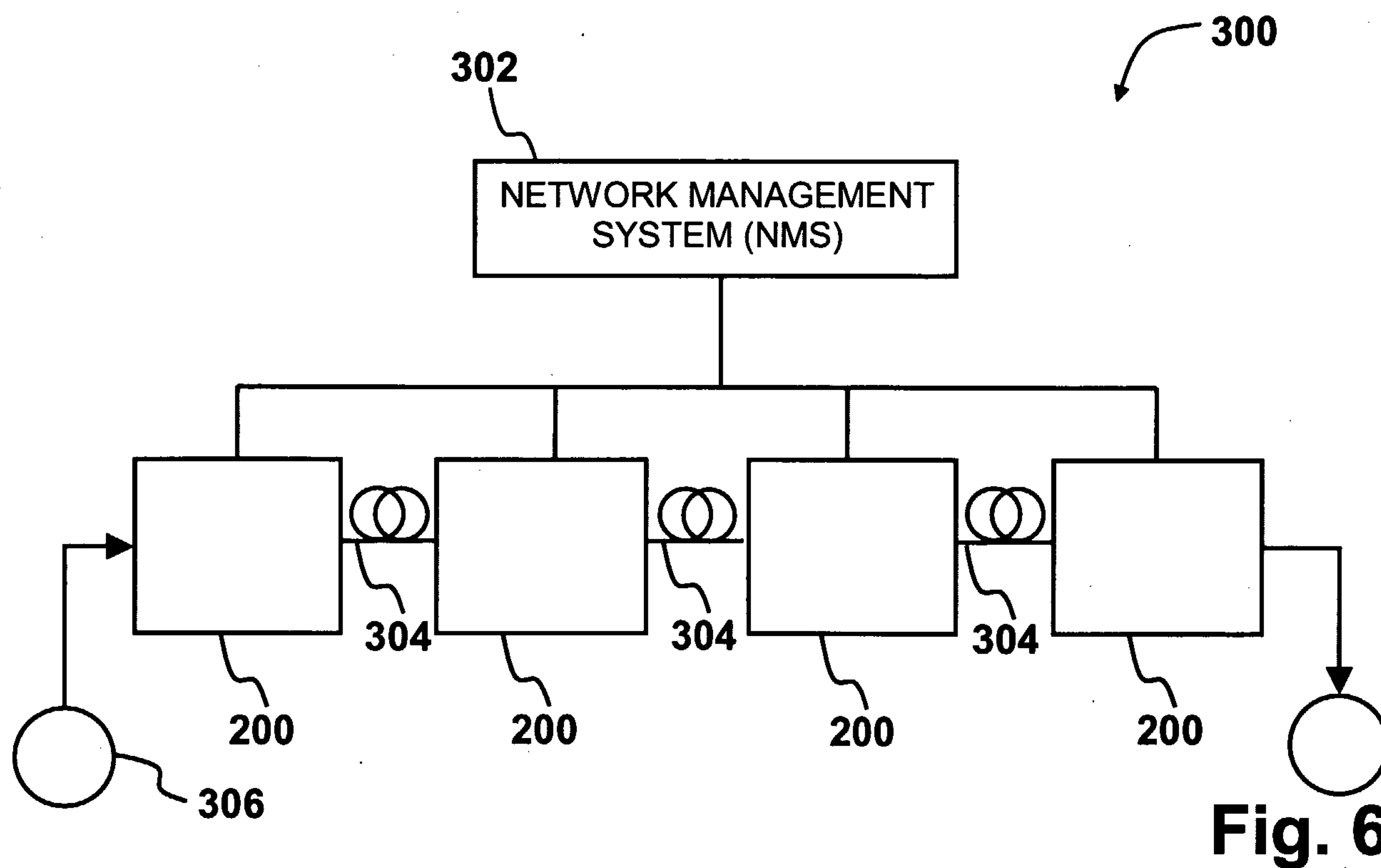


Fig. 7

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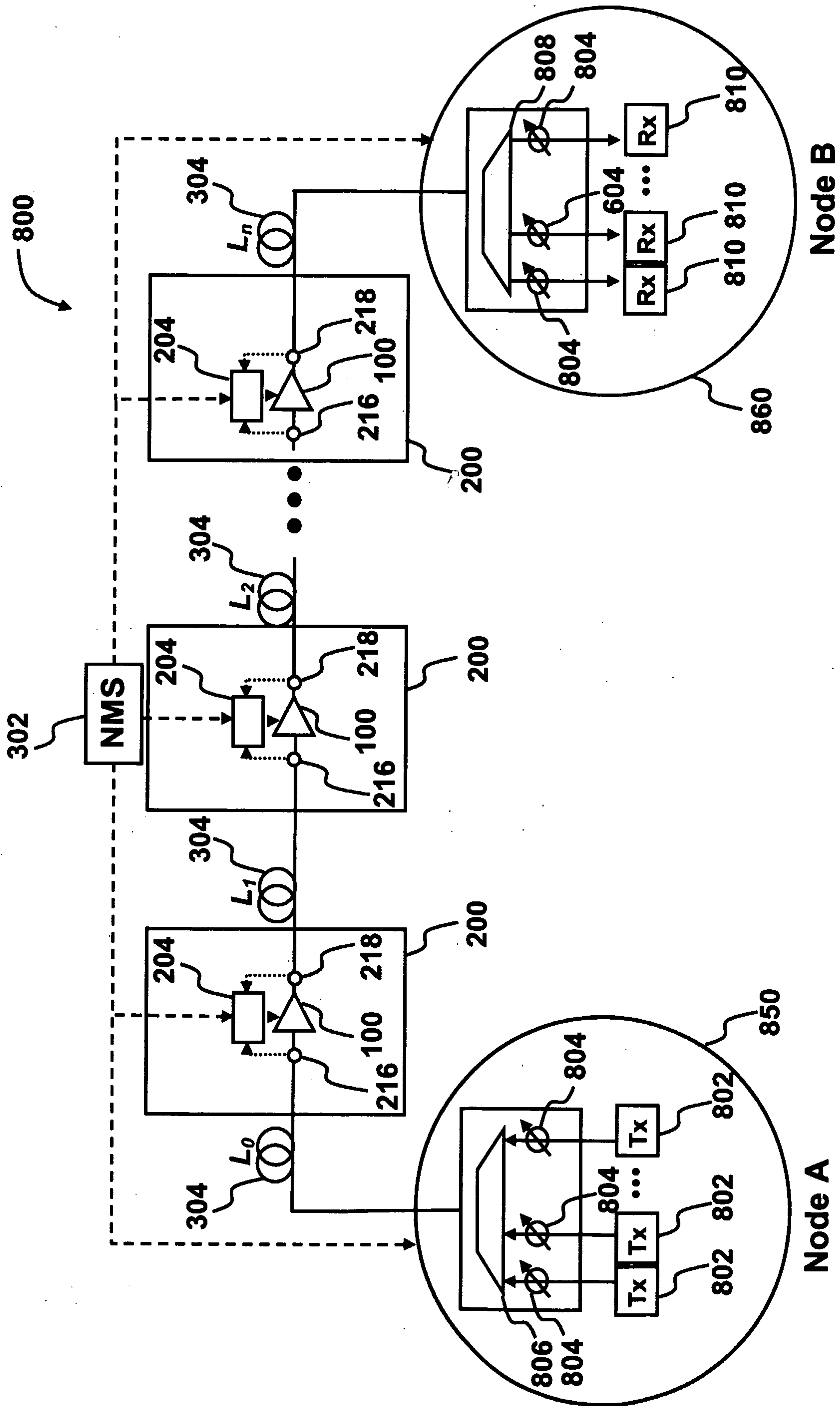


Fig. 8

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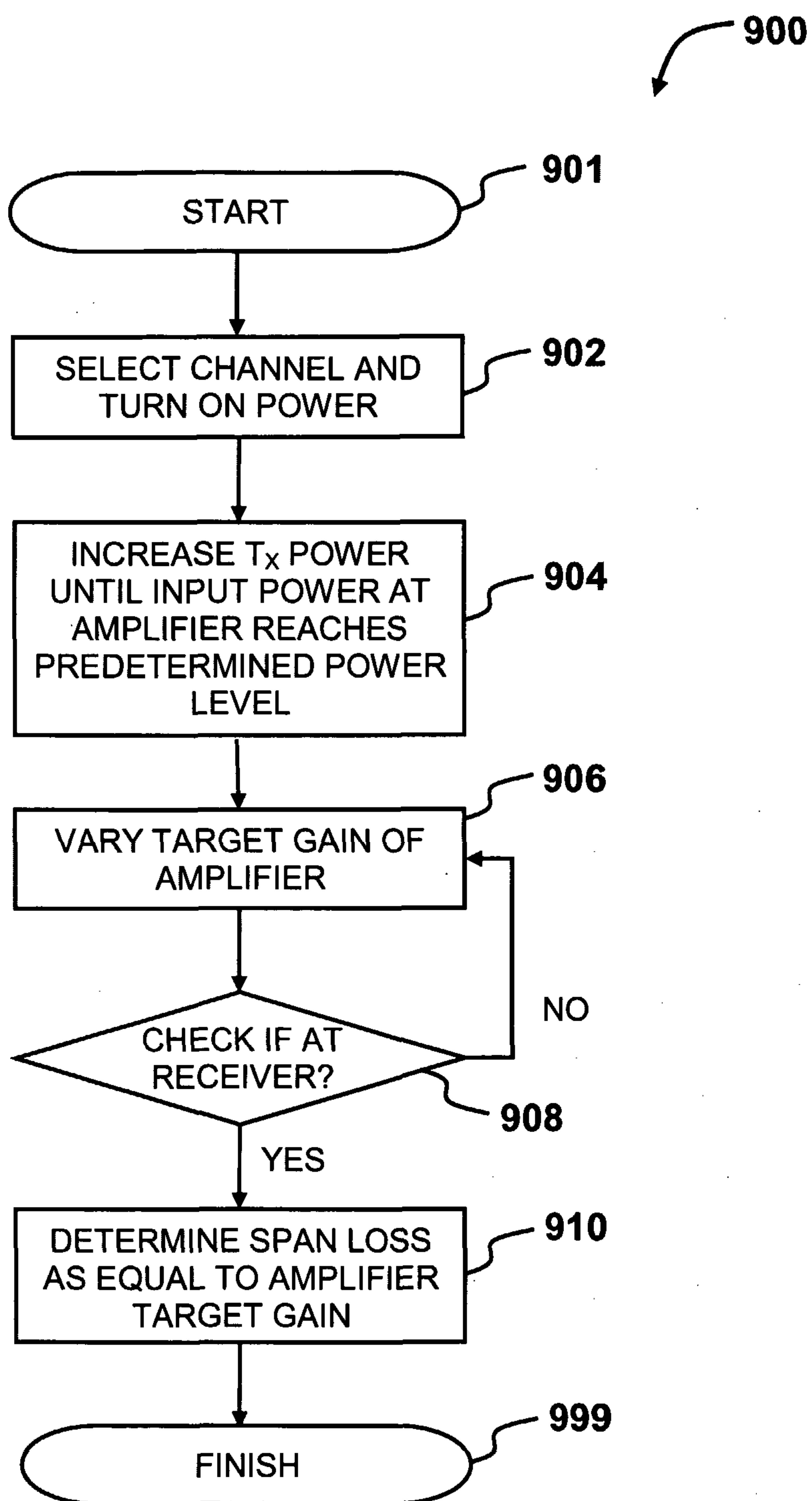


Fig. 9

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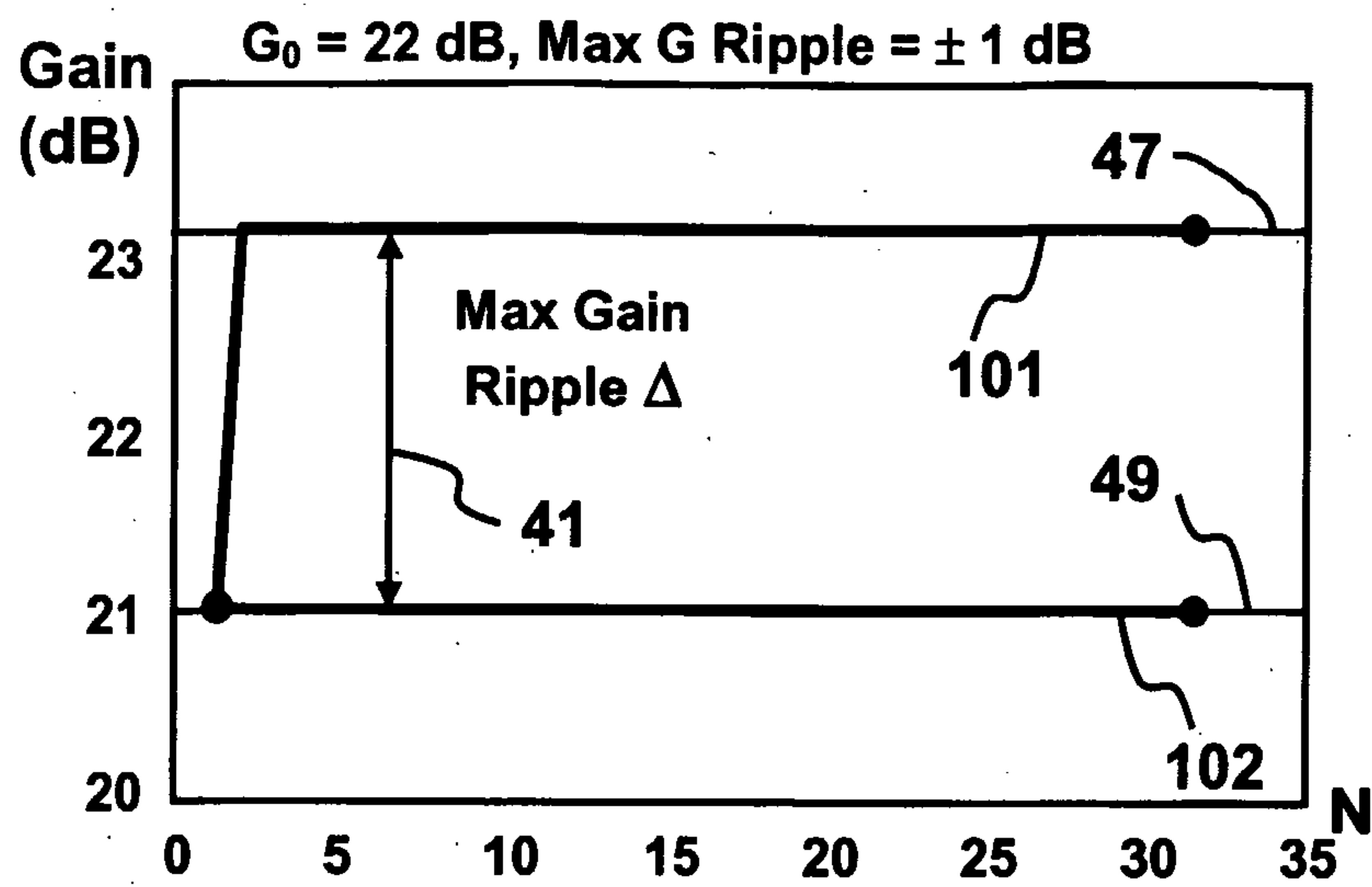


Fig. 10

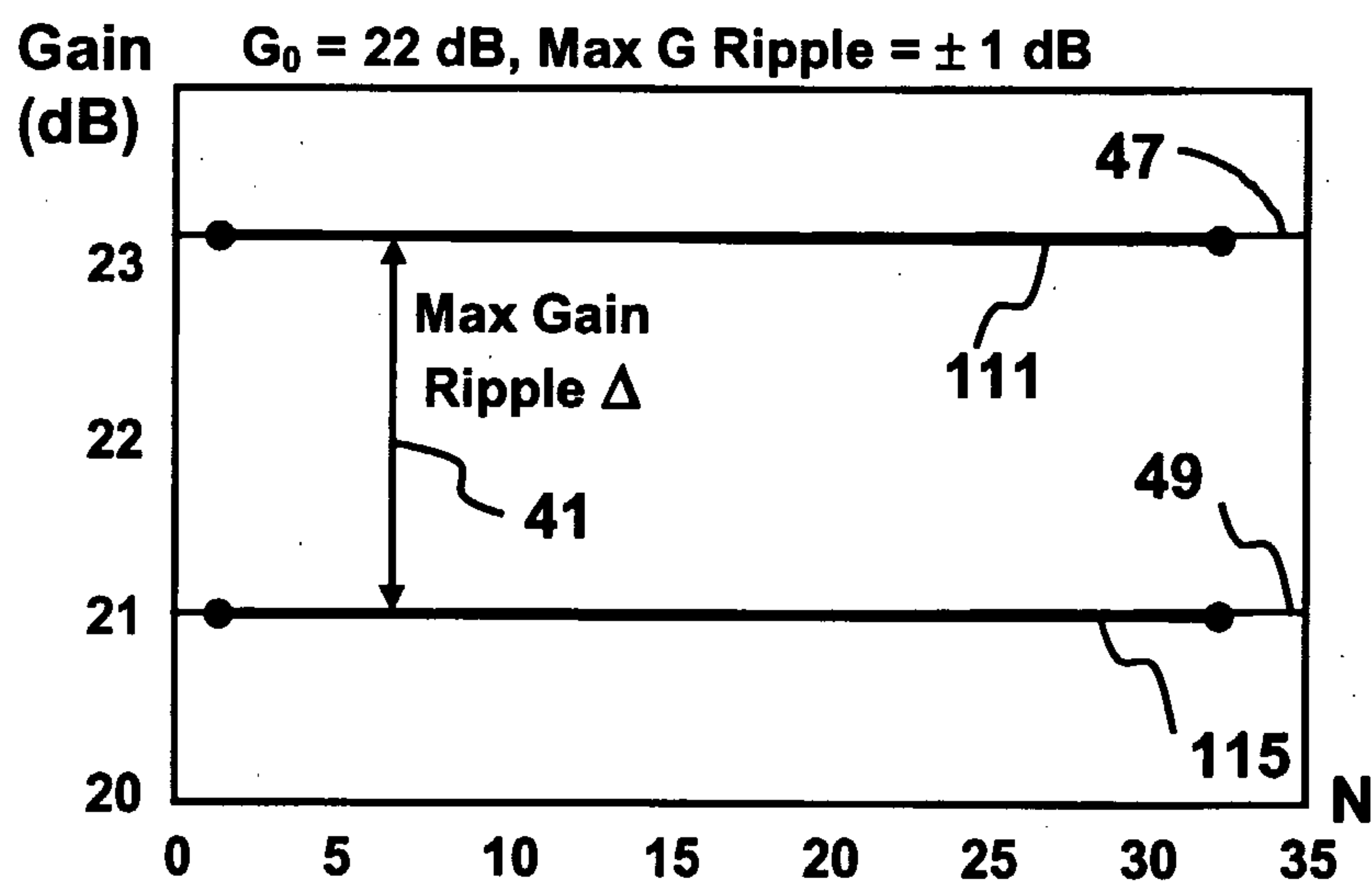


Fig. 11

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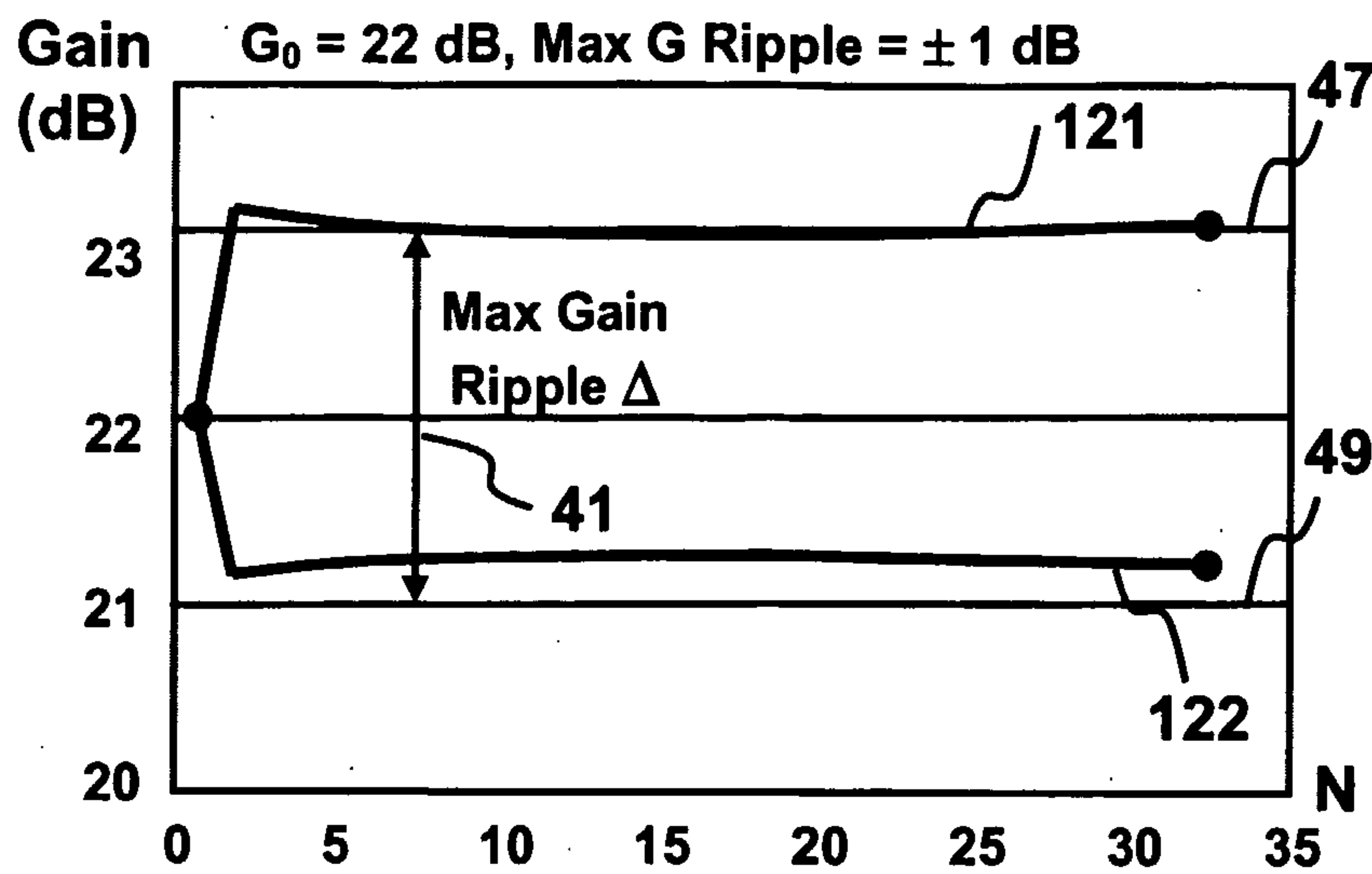


Fig. 12

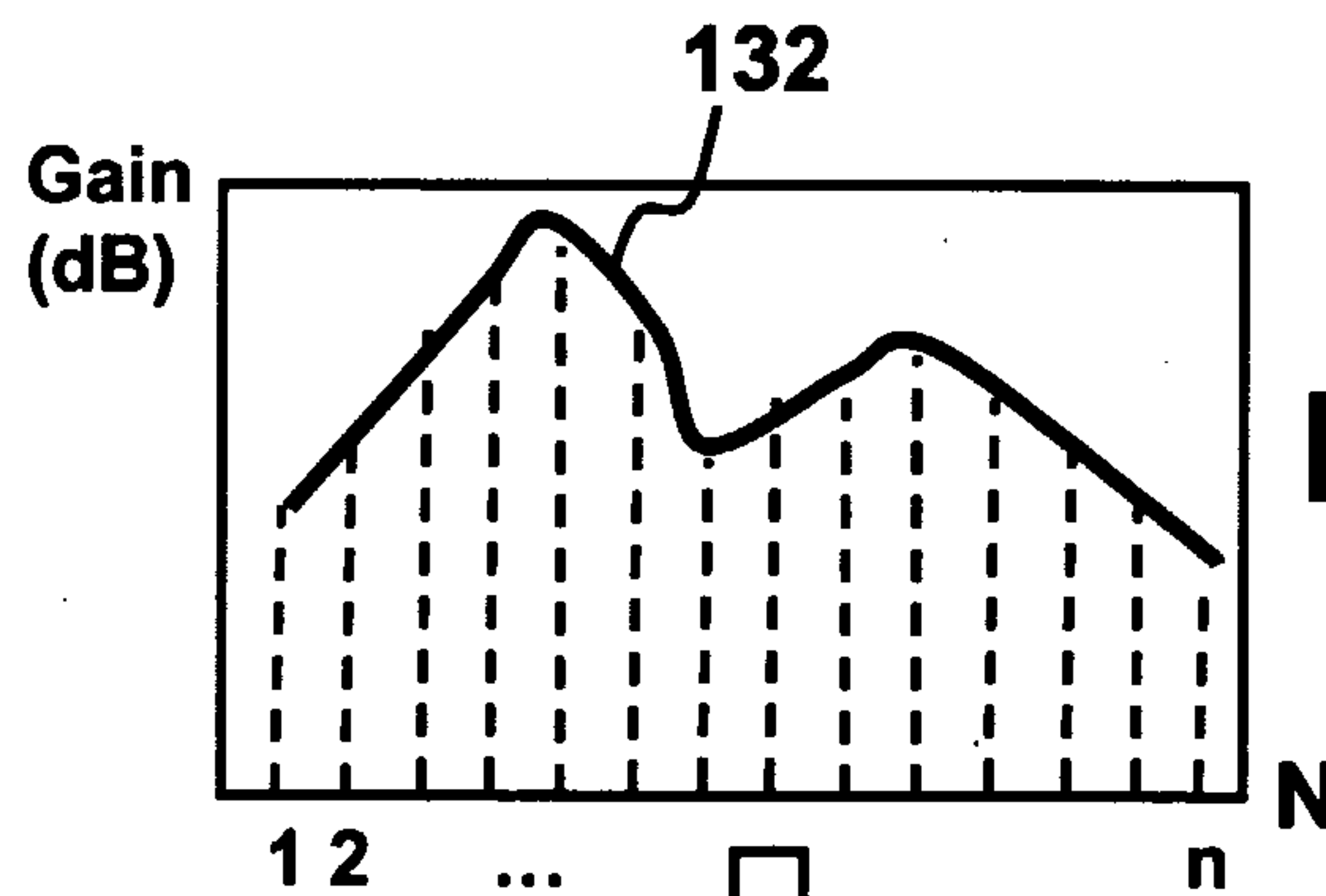


Fig. 13A

Fig. 13B

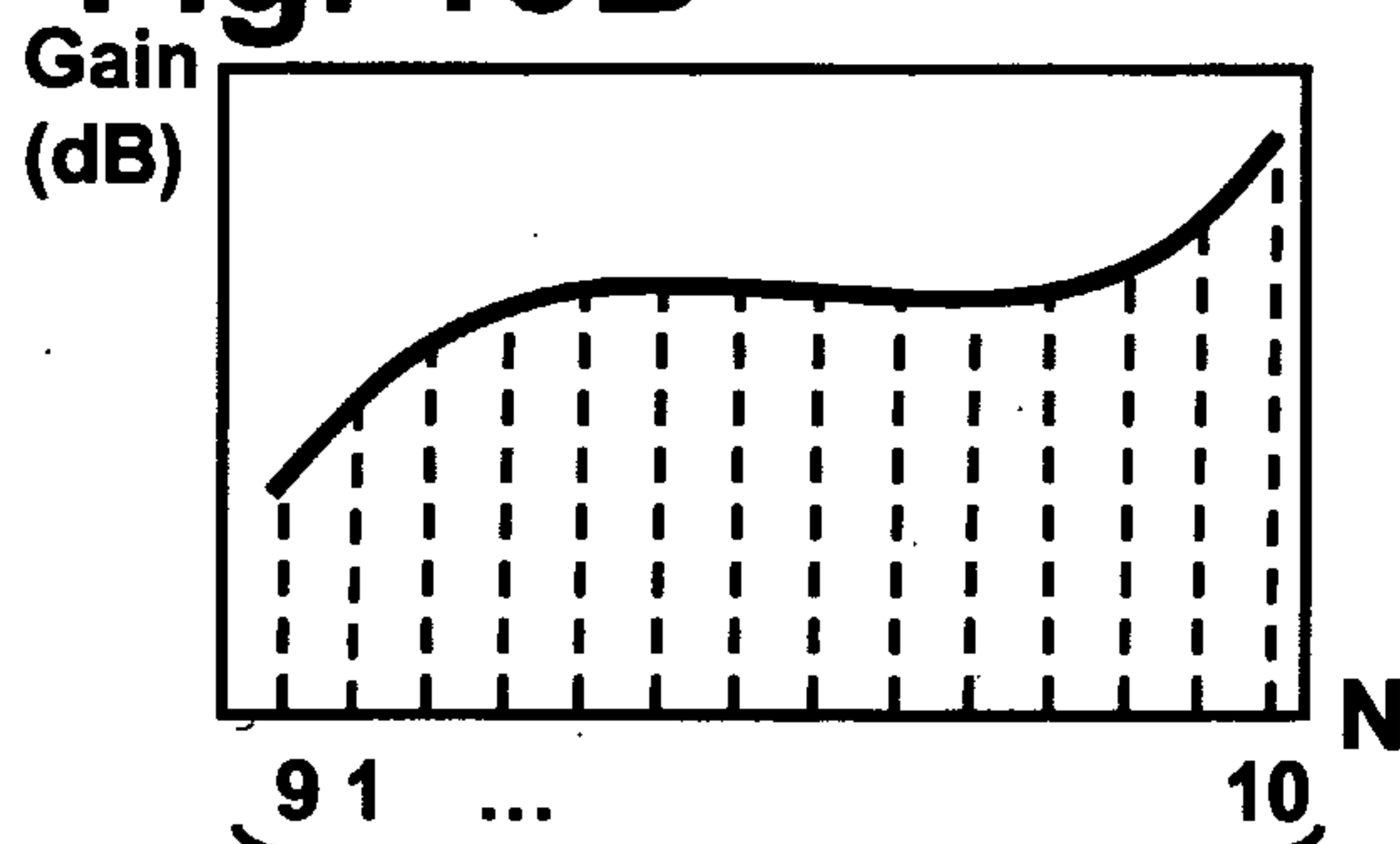
Normalized
Gain (dB)

Fig. 13C

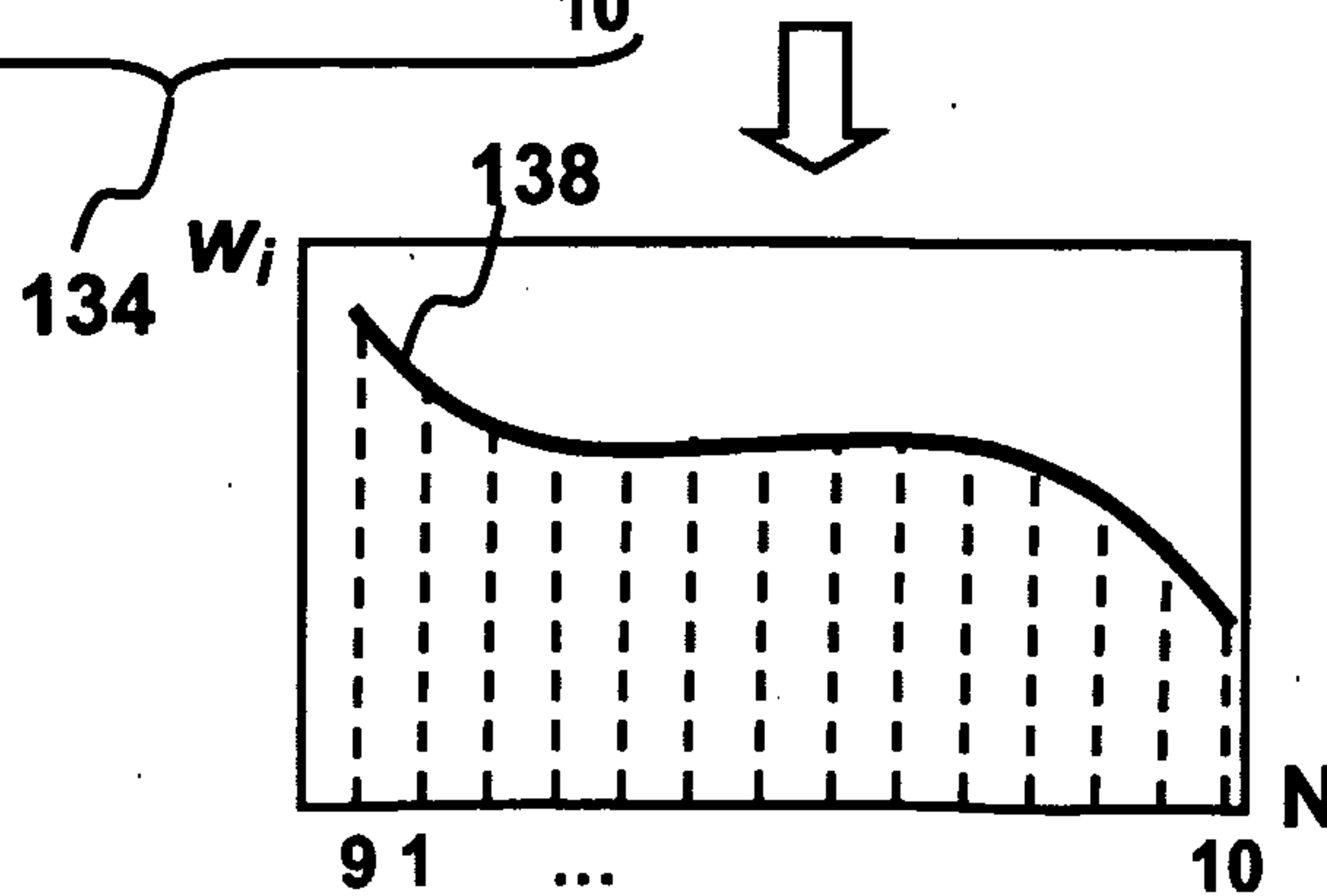
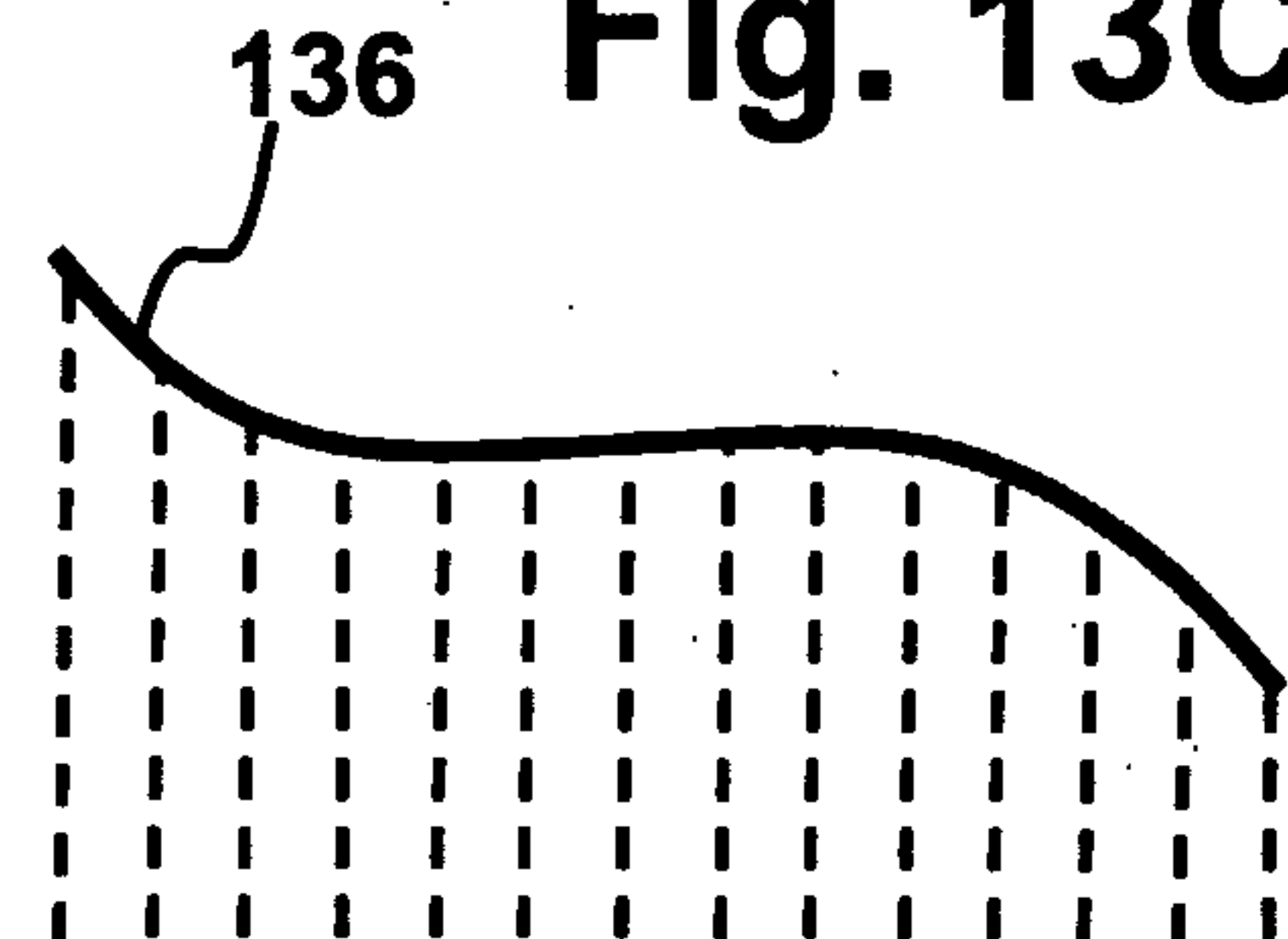
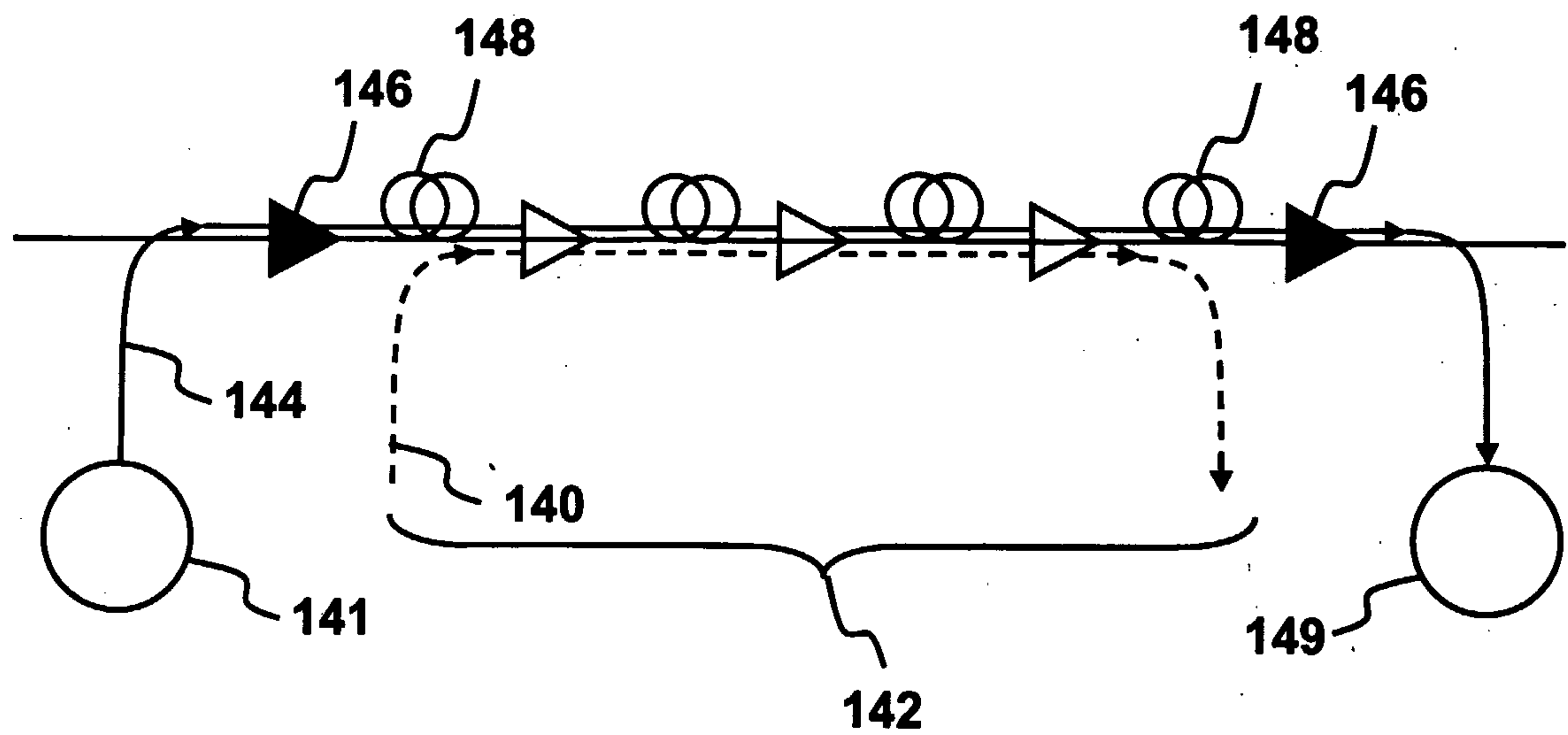
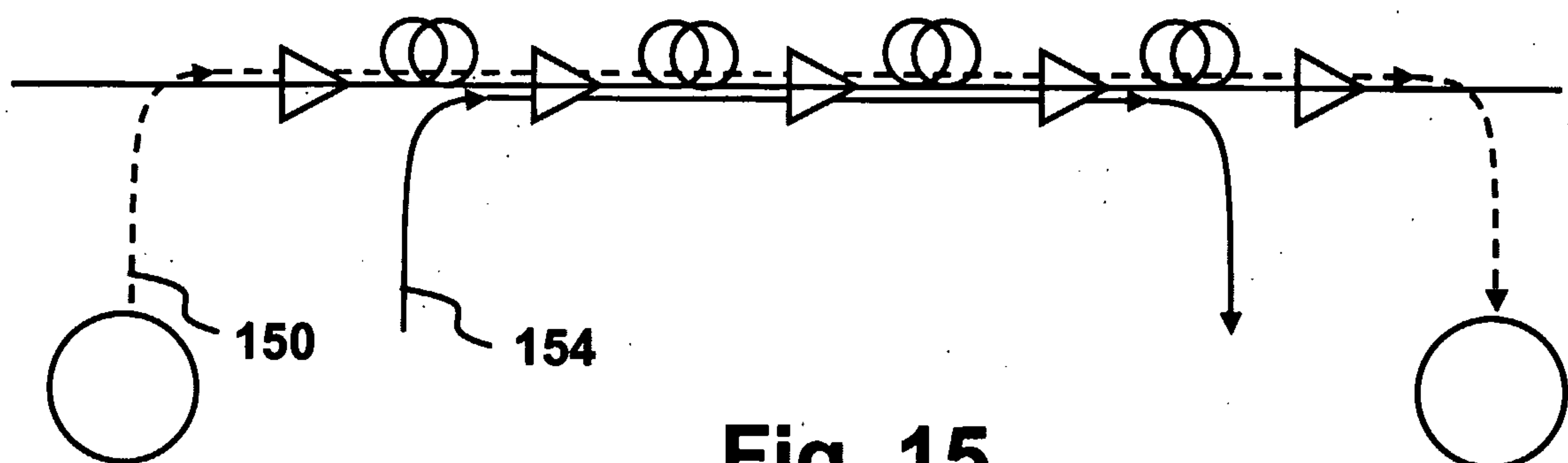


Fig. 13D

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**Fig. 14****Fig. 15**

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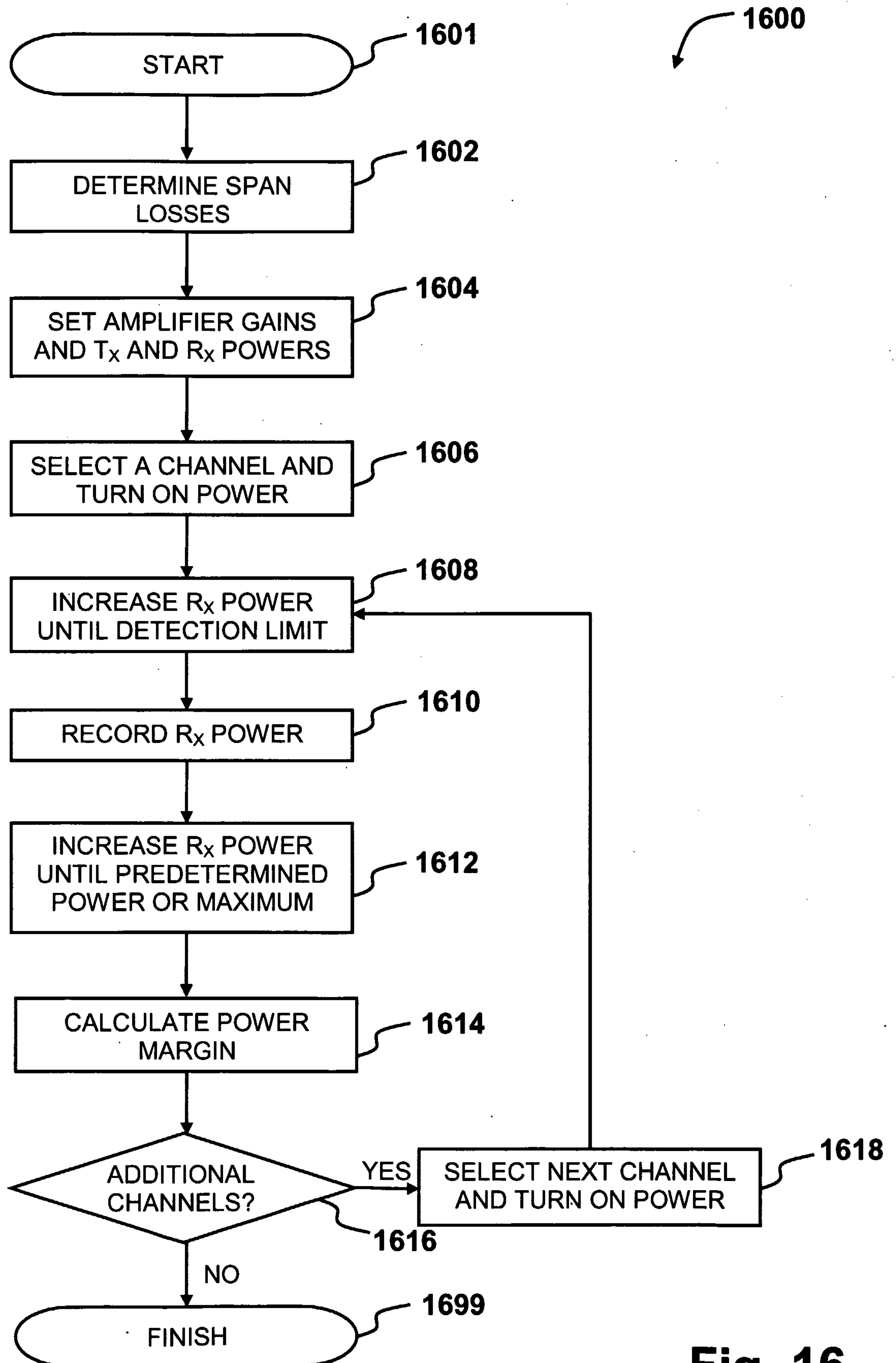


Fig. 16

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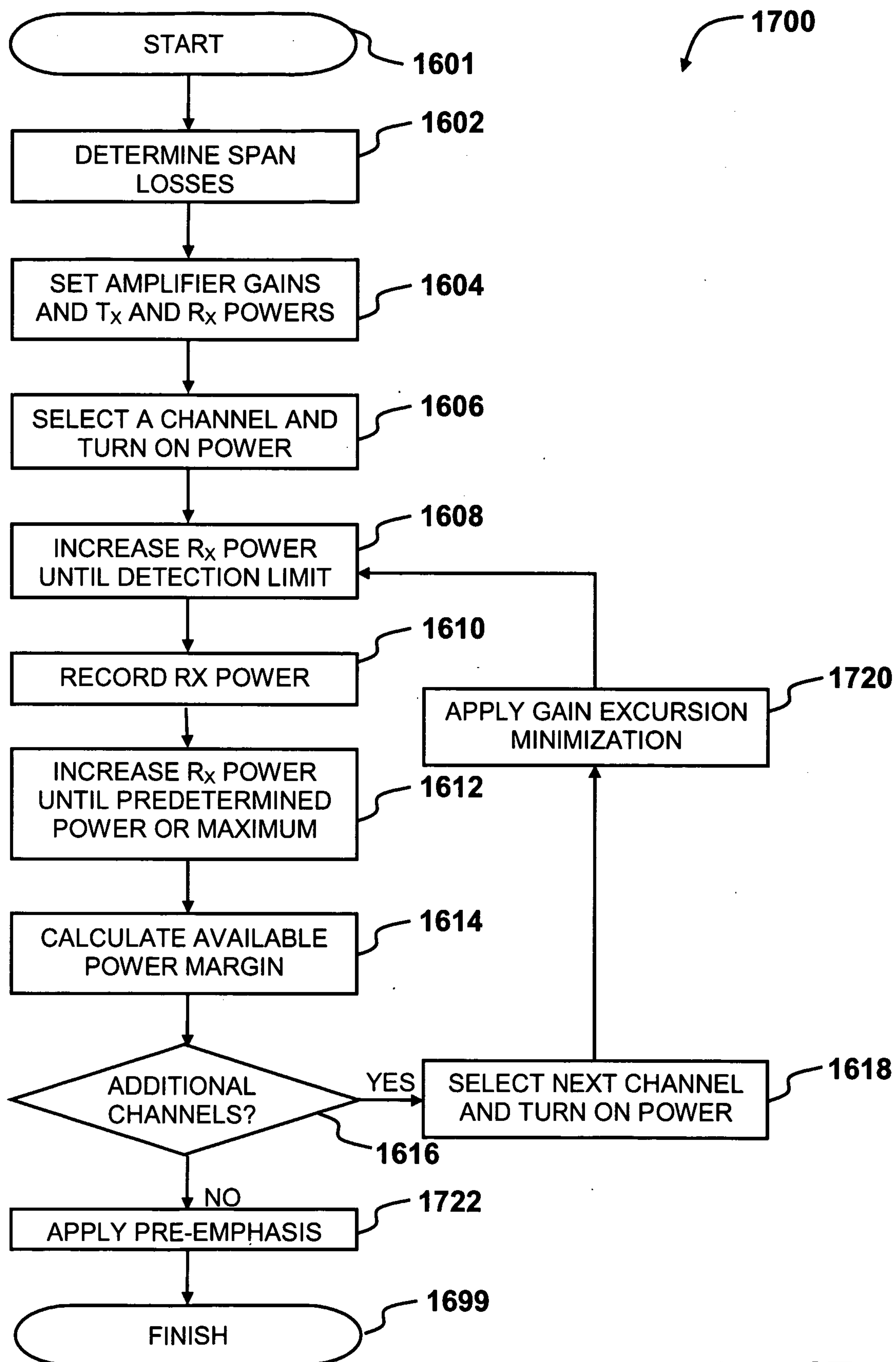


Fig. 17

