

Optical amplifier with improved linearity.

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The invention relates to an optical amplifier comprising a solid-state laser for amplifying an optical input signal to an optical output signal and including a power supply source connected to the solid-state laser for supplying electrical pump energy to the solid-state laser.

5 The invention likewise relates to a transmission system utilizing such amplifiers.

An optical amplifier as defined in the opening paragraph is known from the journal article "Compensation of non-linearity in semiconductor optical amplifiers" by A. Saleh, R. Jopson and T. Darcie in Electronics Letters, July 1988, Vol. 24, No.
10 15, pp. 950-952.

Optical amplifiers are used, for example, in optical transmission systems which utilize glass fibres as a transmission medium. Optical transmission systems are often used nowadays for digital trunk lines between telephone exchanges. Another application is the use in cable television networks for the distribution of analog TV
15 signals over large distances.

The maximum length of a glass fibre which may be covered in one time is restricted by various causes. A first cause for this restriction is the attenuation of the light in the glass fibre transmitted by the transmitter. A second cause is the dispersion of the glass fibre which causes distortion of the pulses transmitted by the transmitter in
20 the case of digital transmission. This pulse distortion occurs as a result of the glass fibre delay being different for light signals having different wavelengths. This pulse distortion is proportional to the length of the glass fibre and, in addition, depends on the spectral width of the transmitted light.

Yet to cover large distances by means of glass fibres, what is commonly
25 referred to as regenerative repeaters are used which are installed equidistantly in the glass fibre. These regenerative repeaters comprise a complete optical receiver which converts the received light signals into digital electric signals. In addition, the regenerative repeater comprises a complete optical transmitter which reconverts the

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digital signals into light signals for further transmission through the glass fibre. Such a regenerative repeater is rather complex.

5 In transmission systems utilizing lasers that generate a light signal with a very small spectral bandwidth, the maximum distance that can be covered will mainly be determined by the attenuation of the glass fibre. In these cases there is no need using a regenerative repeater, but an optical amplifier will be sufficient to amplify the optical signal.

10 Because an optical amplifier, often comprising a solid-state laser as the amplifying element, is much simpler than a regenerative repeater, a considerable saving of costs can be realised in this manner.

A further advantage of the use of an optical amplifier is that its operation is independent on the symbol rate and that the amplifier is capable of simultaneously amplifying light signals having different wavelengths.

15 An important property of an optical amplifier is the linearity of the relation between the optical input signal of the amplifier and the optical output signal of the amplifier.

20 In trunk lines in which various amplitude-modulated optical carriers are utilized, what is commonly referred to as saturation-induced crosstalk occurs. This crosstalk occurs because the actual optical output power per carrier depends on the actual output power of the other carriers due to the non-linearity.

25 Another use of optical amplifiers which demands a proper linearity is the use of optical distribution in cable TV systems. In these systems the signal to be distributed, which may comprise, for example, the entire UHF band (470-860 MHz), is converted into an amplitude-modulated light signal which is distributed through a glass fibre. If non-linear elements such as, for example, a non-linear optical amplifier, are present in this distribution system, noise components resulting from intermodulation may be generated which occur in a desired (TV) channel.

30 In the optical amplifier known from above journal article, a solid-state laser is used as an amplifier element. The electrical pump energy necessary for the solid-state laser is supplied by the power supply source in this case a current source. To improve the linearity of the solid-state laser, the current supplied to the solid-state laser contains not only a DC component but also an additional component which is proportional to the power of the light signal at the input of the solid-state laser.



For generating the additional component of the current supplied to the solid-state laser, however, an optical coupler is necessary for extracting part of the light at the input of the solid-state laser. This extracted light is subsequently to be converted by means of a photodiode into an electric signal which, in turn, is to be reconverted
5 into the additional component of the current for the solid-state laser. The presence of generating means for generating the additional component of the current for the solid-state laser, makes the optical amplifier rather complicated.

It is an object of the invention to provide an optical amplifier as defined in the opening paragraph, having reduced complexity, but retaining the linearity of the
10 prior-art optical amplifier.

For this purpose, the invention is characterized, in that the power supply source is a voltage source.

The invention is based on the recognition that the gain factor of the solid-state laser is mainly determined by the voltage across the active layer of the solid-state
15 laser. For that matter, the voltage across the active layer determines the quasi-Fermi levels in the conduction band and the valence band and thus the density of the load carriers in the two bands. Since the gain of the solid-state laser is determined by this density of load carriers and by a number of constant values, the gain will be constant in the case of a constant density of load carriers in the two bands.

By supplying the solid-state laser from a voltage source *in lieu of* a current source as happens in the prior-art optical amplifier, it is possible to maintain the voltage across the active layer of the solid-state laser and thus the gain at a constant level, irrespective of the value of the optical input signal. In the case of a strong optical
20 input signal the solid-state laser will automatically consume more current from the voltage source to produce the necessary optical output power.

An embodiment of the invention is characterized, in that the voltage source has a negative output impedance.

The use of a voltage source having a negative output impedance makes it possible to maintain the voltage across the active layer of the solid-state laser at a
30 substantially constant level despite the presence of an undesired series resistance in series with the solid-state laser. A possible choice for the absolute value of this negative output impedance is the overall value of the series resistance of the solid-state laser. However, for obtaining the optimum linearity of the optical amplifier, it is conceivable



for the absolute value of the output impedance of the voltage source to be chosen to be greater or smaller than the series resistance of the solid-state laser.

A further embodiment of the invention is characterized, in that the amplifier comprises a temperature measuring means for measuring the temperature of the solid-state laser and includes adjusting means for adjusting the voltage generated by the voltage source in response to the measured temperature of the solid-state laser.

By measuring the temperature of the solid-state laser and giving the voltage generated by the voltage source the proper dependence on the measured temperature, it is possible to render the gain of the optical amplifier independent of the temperature of the solid-state laser.

The invention will now be further explained with reference to the drawing Figures in which like reference characters denote like elements, in which:

Fig. 1 shows a first embodiment of the optical amplifier according to the invention,

Fig. 2 shows a voltage source having a negative output impedance, to be used in an optical receiver as shown in Fig. 1,

Fig. 3 shows a second embodiment of the optical amplifier according to the invention, and

Fig. 4 shows a transmission system according to the invention.

In the optical amplifier as shown in Fig. 1 a glass fibre 1 is coupled to a first facet a of a solid-state laser, in this case a semiconductor laser 2. A second facet b of the semiconductor laser is coupled to a second glass fibre 3.

The anode of the semiconductor laser 2 is connected to a positive terminal of the voltage source 4, the cathode of the semiconductor laser 2 being connected to a negative terminal of the voltage source 4.

The semiconductor laser 2 is arranged on a Peltier element 5. Furthermore, the Peltier element 5 accommodates a temperature sensor 7 for measuring the temperature of the Peltier element 5. The output signal of the temperature sensor 7 is applied to a control circuit 6. An output of the control circuit 6 is connected to the Peltier element 5.

The semiconductor laser 2 in the optical receiver as shown in Fig. 1 has two facets a and b by which the light to be amplified can be captured in the semiconductor laser 2 and the amplified light can be extracted from the semiconductor



laser 2. The semiconductor laser is capable of amplifying both light captured on facet a and light captured on facet b. In many cases the semiconductor laser 2 is symmetrical, which means that the two facets present the same reflectivity.

5 The operation and structure of semiconductor lasers as well as the materials suitable for manufacturing semiconductor lasers are described in the book entitled "Physics of Semiconductor Devices" by S.M. Sze, chapter 12, John Wiley & Sons, Inc. 1981. The use of semiconductor lasers for amplifying optical signals is known from the journal article "Semiconductor Laser Optical Amplifiers for Use in Future Fiber Systems" by M.J. O'Mahony in Journal of Lightwave Technology, Vol. 6, 10 No. 11, April 1988.

By utilizing, in accordance with the inventive idea, a voltage source 4 as the power supply source for supplying electrical pump energy to the semiconductor laser 2, there is achieved that the gain of the semiconductor laser becomes less dependent on the power of the optical signal to be amplified than in the case of a 15 semiconductor laser which is supplied, as is customary, with a DC current. As a result, the complex compensation means for enlarging the current flowing through the semiconductor laser as discussed in above journal article by Saleh, Jopson and Darcie are no longer necessary.

20 The voltage V is to be selected such that the current I , in the absence of a light signal to be amplified, continues to be below the threshold current of the semiconductor laser 2 so as to avoid undesired oscillation of the semiconductor laser 2.

To avoid the gain of the semiconductor laser 2 changing as a result of temperature variations, the temperature of the semiconductor laser 2 is maintained at a constant level. This is done with the aid of a Peltier element 5 which accommodates a 25 temperature sensor 7 for measuring the temperature of the Peltier element 5. If the temperature of the Peltier element 5, and thus also of the semiconductor laser 2, deviates from the desired value, the control circuit 6 will send an electric current through the Peltier element 5 for cooling this down if the measured temperature is too high, and for heating it up if the measured temperature is too low. A suitable operating 30 temperature of the semiconductor laser 2 is, for example, 20°C .

In the voltage source 4 shown in Fig. 2 a first terminal of a reference voltage source 10 carrying a voltage value V_{ref} is connected to a first terminal of a resistor 12 having a resistance R . A second terminal of the resistor 12 is connected to a



first terminal of a resistor 14, likewise having a resistance R , and to a non-inverting input of a differential amplifier 18.

A second terminal of the resistor 14 is connected to a first terminal of a resistor 16 having a value R_d and to the output of the differential amplifier 18. A second terminal of the resistor 16 is connected to an inverting input of the differential amplifier 18 and to a first terminal of a capacitor 20. A second terminal of the reference voltage source 10 is connected to a second terminal of the capacitor 20. The voltage for the semiconductor laser 2 is now available between the first and second terminals of the capacitor 20.

The voltage source as shown in Fig. 2 is a voltage source having a negative output impedance according to the inventive idea. For deriving the voltage V from the voltage V_{ref} and current I , to be discussed hereinafter, the effect of the capacitor 20 is discarded. If the gain of the differential amplifier 18 is sufficiently large, this differential amplifier 18 may be assumed to cause the voltage difference between the inverting input and the non-inverting input to be zero.

Based on this assumption the voltage on both the inverting and the non-inverting input may be set equal to V . For the output voltage V_u of the differential amplifier 18 the following comparisons may be written:

$$V_u = V + I \cdot R_d \quad (1)$$

$$\frac{V_u - V}{R} = \frac{V - V_{ref}}{R} \quad (2)$$

By substituting (1) in (2) and eliminating V_u , the following will be found:

$$V = V_{ref} + I \cdot R_d \quad (3)$$

From (3) it appears that a voltage source having a negative output impedance is indeed obtained, as a result of which the output voltage increases with enhancing current I . If, according to the inventive idea, the value R_d is made equal to the series resistance of the semiconductor laser, it is possible to obtain a DC voltage across the active layer of the semiconductor laser. It is conceivable that a slightly larger or slightly smaller value of R_d entails a better linearity of the optical amplifier, because the relation between the voltage across the active layer and the gain is based on simulation models.



The capacitor 20 is incorporated for rapidly supplying the necessary additional current for the semiconductor laser 2 in the case where the power of the optical input signal of the optical amplifier enhances rapidly. The differential amplifier is often incapable of supplying this additional current sufficiently rapidly.

5 In the optical amplifier shown in Fig. 3 a first glass fibre 34 is coupled to a first facet of the solid-state laser, in this case a semiconductor laser 30. A second glass fibre 36 is coupled to a second facet of the semiconductor laser 30.

A temperature measuring means, a temperature sensor 38 in this case, is connected to the semiconductor laser 30 to measure the temperature of the semiconductor laser 30. The output signal of the temperature sensor 38 is applied to an input of an analog-to-digital converter 46. The output of the analog-to-digital converter 46 is connected to a first input port of the adjusting means, in this case a microprocessor 40. An output port of the microprocessor 40 is coupled to an input of the voltage source, in this case a digital-to-analog converter 44.

15 The anode of the semiconductor laser 30 is connected to a first terminal of a resistor 32 and to a first input of an analog-to-digital converter 42. A second terminal of the resistor 32 is connected to a second input of the analog-to-digital converter 42 and to a first output of the digital-to-analog converter 44. A second output of the digital-to-analog converter 44 is connected to the cathode of the semiconductor laser 30. 20 An output of the analog-to-digital converter 42 is coupled to a second input port of the microprocessor 40.

By measuring the temperature of the semiconductor laser 30 it is possible, according to the inventive idea to make the voltage produced by the voltage source dependent on the temperature of the semiconductor laser 30 so as to make the gain of the optical amplifier independent of the temperature.

25 For this purpose, the microprocessor 40 stores the relation between the voltage necessary for the semiconductor laser 30 and the temperature at a constant gain. This relation may be stored in the microprocessor 40 by way of a Table or by way of a formula determined by curve fitting.

30 Establishing this relationship requires a single measurement of the necessary voltage as a function of temperature at a constant gain. It is conceivable to carry out calibration measurements periodically and to adjust the relation stored in the microprocessor 40 to compensate for the effect of ageing of the semiconductor laser 30.



To give the voltage source formed by the digital-to-analog converter 44 a negative output impedance, it is necessary to measure the current flowing through the semiconductor laser 30. This is performed by converting, with the aid of the analog-to-digital converter 42, the voltage across resistor 32 into a digital signal used for
5 increasing the output voltage of the digital-to-analog converter 44 in the case where there is an enhancing current through the semiconductor laser 30.

If the response rate of the microprocessor 40 to variations in the required current is too low, the voltage source having negative resistance as shown in Fig. 2 may rather be used *in lieu of* the resistor 32 in combination with the analog-to-digital
10 converter 42. The voltage source 10 shown in Fig. 2 is then formed by the digital-to-analog converter 44.

In the transmission system as shown in Fig. 4 an optical transmitter 50 is coupled to an optical receiver 59 through glass fibres 51, 54 and 57. Between the glass fibres 51 and 54 an optical amplifier 53 according to the inventive idea is inserted.
15 Between the glass fibres 54 and 57 an optical amplifier 56 according to the inventive idea is inserted. In addition, the supply lines 52, 55 and 58 are inserted between the optical transmitter 50 and the optical receiver *via* the optical amplifiers 53 and 56.

The light transmitted by the optical receiver 50 is transported through the glass fibre 51 to the optical amplifier 53 and amplified there. The amplified optical
20 signal is transported through glass fibre 54 to the optical amplifier 56, amplified there, and then transmitted to the optical receiver 59. The electrical energy necessary for the optical amplifiers is conveyed to the respective optical amplifiers through the connections 52, 55 and 58.

Claims:

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1. Optical amplifier comprising a solid-state laser for amplifying an optical input signal to an optical output signal and including a power supply source connected to the solid-state laser for supplying electrical pump energy to the solid-state laser, characterized in that the power supply source is a voltage source.
- 5 2. Optical amplifier as claimed in Claim 1, characterized in that the voltage source has a negative output impedance.
3. Optical amplifier as claimed in Claim 2, characterized in that the absolute value of the output impedance of the voltage source is equal to the series resistance of the solid-state laser.
- 10 4. Optical amplifier as claimed in one of the preceding Claims, characterized in that the amplifier comprises a temperature measuring means for measuring the temperature of the solid-state laser and includes adjusting means for adjusting the voltage generated by the voltage source in response to the measured temperature of the solid-state laser.
- 15 5. Optical transmission system comprising an optical transmitter coupled to an optical receiver *via* at least an optical amplifier, the optical amplifier comprising a solid-state laser for amplifying an optical input signal to an optical output signal and including a power supply source which is connected to the solid-state laser for supplying electrical pump energy to the solid-state laser, characterized in that the power supply
- 20 source is a voltage source.
6. Optical transmission system as claimed in Claim 5, characterized in that the voltage source has a negative output impedance.
7. Optical transmission system as claimed in Claim 6, characterized in that the absolute value of the output impedance of the voltage source is equal to a series
- 25 resistance of the solid-state laser.
8. Optical transmission system as claimed in one of the Claims 5, 6 or 7, characterized in that the amplifier comprises a temperature measuring means for measuring the temperature of the solid-state laser and includes adjusting means for

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adjusting the voltage generated by the voltage source in response to the measured temperature of the solid-state laser.



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