



166166

High power semiconductor laser apparatus with improved fiber coupling efficiency and laser spectrum

BACKGROUND OF THE INVENTION

1. FIELD OF THE INVENTION

The present invention relates to a high power pump laser apparatus. It particularly concerns with the high power optical pumping of an optical amplifier, such as Erbium doped fiber amplifier and Raman amplifiers, to achieve an enhanced system performance.

2. DESCRIPTION OF THE RELATED ART

The use of laser diode light source which is capable of providing high optical output power is becoming highly desirable in optical communications systems. There is an increasing demand for pumping sources for Raman amplifiers and the high power erbium-doped fiber amplifier (EDFA) in future dense wavelength division multiplex (DWDM) systems. The EDFA's are commonly pumped at about 1480 nm, i.e. the emission wavelength of a commercially available laser, and they may also be pumped with a source matched to the 980 nm erbium absorption line. The EDFA makes it practical to increase span lengths between regenerators to suit most terrestrial and underwater needs due to its low noise figure. The gain bandwidth of such amplifier is sufficient to permit simultaneous amplification of multiple channels for dense wavelength division multiplexing purposes.

A laser diode consists of a planar semiconductor waveguide with the end facets cleaved to form the resonator mirrors. The beam profile in the fast axis of the aperture is defined by the waveguide index profile of the semiconductor material, whilst in the slow axis, the emitting aperture is defined by the stripe width. The stripe



G00001

width is usually limited to a few micrometers to ensure operation in a single transverse mode with good beam quality. If the output power exceeds about 150 milliwatts, such a small aperture leads to high power densities that can result in optical damage. To make use of a plurality of laser diodes together with a multi-channel optical coupler is therefore a possible approach to achieving higher power output, say greater than one watt. Such approach also permits a much broader operating bandwidth.

In applications that require laser emissions at a single predetermined wavelength, it is necessary to stabilize the operating wavelength of the laser. A practical technique for the wavelength control is to filter the light emitted from the laser source and feed the filtered light back to the laser cavity. This feedback mechanism for wavelength control can result in a favored resonance at the filtered bandwidth, which dominates the laser output. Accordingly, such feedback can cause the laser to oscillate at a single predetermined wavelength, and is therefore called wavelength selective feedback. In the case of laser diodes, this feedback may be provided from external optics, thereby forming an external cavity laser. In one form of external cavity laser, an optical signal is output from the laser, collimated with a lens, and coupled to an optical fiber containing a Bragg grating. The grating provides a narrow band reflected signal that is spatially matched to the optical mode of the fiber, and that can be coupled back to the diode with the lens to form an external resonant cavity. Fiber Bragg grating can be used to achieve quasi-monochromatic light sources which are desirable in many practical applications. In this technique, the fiber Bragg grating acts as a phase-preserving mirror when the Bragg condition is met precisely. The U.S. Patent No. 6,188,705 to Krainak et al, disclosed the fiber grating coupled quasi-monochromatic light sources capable of tunable single frequency operation. The currently preferred method of recording an in-line grating in optical fiber is to subject a photosensitive core to the interference pattern between two beams of actinic (typically UV) radiation passing through the photoinsensitive cladding. The U.S. Patent No. 5,327,515, to Anderson et al., disclosed a method of recording Bragg gratings in single mode optical fibers by UV exposure through a phase mask.

In addition to control wavelength fluctuations, it is also necessary to maintain the beam quality in the slow axis for the broad area lasers. A number of schemes have

been proposed for this purpose. One approach is to take the diffraction-limited output of a narrow stripe master oscillator and to amplify it to the required power in a semiconductor amplifier. Ideally, the beam quality of the master oscillator is preserved in the amplifier, providing a high power diffraction-limited output. This kind of optical device takes the form of an integrated master oscillator and power amplifier (MOPA), in which the master oscillator and the tapered power amplifier are integrated monolithically into a single chip. The structure of the device is complex. For example, it requires separate current sources for the master oscillator and for the amplifier. The currently available devices of this kind exhibit relatively short lifetimes, and their practical uses are therefore limited. An alternative technique involves modification of the laser resonator to support a larger optical mode. In a conventional resonator, the transverse mode is determined by the mirror curvature, the resonator length and the intra-cavity lens determined by a variety of thermal and carrier-density effects. One technique for increasing the mode size in a semiconductor laser is to replace the planar cleaved facets with convex reflectors, giving an unstable resonator semiconductor laser. Relatively large output powers with good beam quality can be achieved with this technique. However, as the process to produce the required high quality curved reflector is difficult and expensive, the applications of the devices are also limited.

One other approach is described by Emori, et al, in "Broadband lossless DCF using Raman amplification pumped by multichannel WDM laser diodes" in Electronics Letters, vol. 34, No. 22, pp. 2145-2146, for the development of the broadband dispersion compensation Raman amplifier (DCRA). The device consists of a number of single emitter laser diode modules. Each laser is stabilized by a fiber Bragg grating, and is polarized and wavelength combined by a wavelength division multiplexing (WDM) coupler, resulting in a total of eight lasers pumping the dispersion compensating fibre (DCF). The total maximum output power is greater than 1.0W. Emori also described a 100 nm bandwidth Raman amplifiers using 12-wavelength-channel combined by a WDM coupler for broadband Raman amplification, referring to Y. Emori, K. Kanaka, and S. Namiki, "100nm bandwidth flat-gain Raman amplifiers pumped and gain-equalized by 12 wavelength-channel WDM laser diode unit" in Electronics Letters, vol. 35, No. 16, pp. 1355-1356. The WDM coupler is a silica-based planar lightwave circuit (PLC) comprising 11 Mach-

Zehnder interferometers (MZIs). The Mach-Zehnder, which served as a wavelength selective coupler, relies on the precisely controlled phase difference between two interferometer arms and is highly sensitive to environmental fluctuations and manufacturing variations. In addition, a significant fraction of the input signal is back reflected. One of the other drawbacks of this approach is its large channel spacing. Therefore, it is uncertain whether this device will be able to meet the demanding reliability requirements for telecommunications components.

SUMMARY OF THE INVENTION

It is the general object of the present invention to provide a pump laser light source suitable for use in high power EDFA and Raman amplification. The high quality laser source is featured with improved performance, i.e., high gain, high saturation output power (e.g. $> 1\text{W}$), low noise figure, and high stability in terms of wavelength and output power. It is a further objective of the invention to provide a laser light source with narrow laser spectrum width, e.g. 1 nm .

The device described in the present invention comprises of an arrayed laser diode emitters and an arrayed waveguide grating (AWG) having a plurality of input channel waveguides and at least one output channel waveguide. Each of the light emitter is coupled with an input channel waveguide that is adapted for a predetermined wavelength. In accordance with the present invention, means are provided to lock the wavelength of the light emitted from each emitter by a fibre Bragg grating at the input channel of the AWG. An AWG multiplexer consists of two star couplers combined with a waveguide array acting as a diffraction grating. The waveguide array is integrated with input waveguides, output waveguides, and two concave slab waveguides acting as star couplers. The integrated AWG multiplexer has been successfully fabricated by several waveguide technologies such as silica waveguides on a silicon or silica substrate and InGaAsP waveguides on an InP substrate. The AWG multiplexer can be designed to route channel from in-port to out-port. An N -channel WDM signal with equal channel space injected from an input waveguide can be divided and distributed into the corresponding output waveguide

according signal wavelength, due to the diffraction of the arrayed waveguide. In the present invention, the input channel waveguides of the AWG are adopted for a plurality of wavelengths ($\lambda_1, \lambda_2, \dots, \lambda_i, \dots, \lambda_n$), being within the bandwidth of the said light emitter of the laser diode array. The wavelength spacing between the input channel waveguide, $\Delta\lambda_i = \lambda_i - \lambda_{i-1}$, is substantially constant.

Since a laser diode array is used, and the light power from each emitter is gathered by a WDM coupler in the present invention, high power can easily be obtained. As the wavelength from each emitter is locked by a Fiber Bragg Grating (FBG), stability of the present proposed laser diode is maintained. In addition, since spectrum width of the laser is determined by the FBG, the total spectrum width can be preset at a small value. To enhance coupling efficiency between laser emitter and the WDM coupler, waveguide of each emitter with a tapered aperture is proposed in the present invention. This structure can further increase the light power from the laser diode.

Other objectives and attainments together with a fuller understanding of the invention will become apparent and appreciated by referring to the following description and claims taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features of the present invention will be more fully apparent by reference to the following detailed descriptions in conjunction with the drawings in which

- FIG.1 shows a prior art high power light source.
- FIG.2 shows a simplified schematic drawing of a pump light apparatus incorporating an array waveguide in accordance with one embodiment of the present invention.
- FIG.3 shows a simplified diagram of the divergent emission effect.

FIG.4 shows a simplified diagram of a pump light source incorporating a lens array between the laser diode array and the input channel waveguide of AWG.

FIG.5 (a) shows a simplified schematic drawing of a light emitter incorporating a spot-size converter, and

FIG.5 (b) shows an alternative spot-size converter of the light emitter.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

A brief description of the prior art high power light source is provided hereinafter in order to develop a better understanding of the present invention and its departure from the prior art. **Fig. 1** shows a prior art pump laser diode unit having a twelve-wavelength-channel WDM coupler. The device comprises high power GRINSCH strained layer multi-quantum well (MQW) buried heterostructure (BH) laser diode modules **11**. The wavelength of the single emitter laser diodes ranges from 1405 to 1510 nm to enlarge the gain bandwidth of Raman amplifiers. Each laser is stabilized by a fiber Bragg grating **12**, to have a narrow and stable spectrum for low insertion loss through the WDM coupler **14**. The WDM coupler is a silica-based planar lightwave circuit (PLC) comprising 11 Mach-Zehnder interferometers (MZIs). A polarization beam combiner (PBC) **13** is used for each channel of the WDM coupler to combine the polarization-multiplexed laser diodes. Since Raman gain obtained with a single wavelength pump is about 20nm wide, less than 20nm wavelength spacing of WDM pump is necessary to smooth out and flatten the gain. To obtain a flat, broadband, and high Raman gain in a single fiber output **15**, using WDM pumping, more energy is allocated to the shorter wavelength range of pumping. Whilst it is to appreciate that the laser diode unit based on MZI type WDM pumping may achieve a higher maximum output power, say greater than 1.0W. it also suffers from several drawbacks. Its performance stability is of great concern in industry applications. Due to the relatively large channel spacing, the total number of the single emitter laser diodes is limited, which in turn limits the total maximum power output for this type of device. Furthermore, integration of the Mach-Zehnder

interferometers in series using planar lightwave circuit technology is costly and results in a relatively large device size.

Referring to **FIG. 2**, a high power light source apparatus is schematically shown in accordance with one embodiment of the present invention. The high power light source comprises of a laser diode array **17** having a plurality of light emitters **18**, and an arrayed waveguide grating (AWG) **19**. The AWG **19** is disposed on a substrate **20**, which is typically made of InP wafer, and has a plurality of input channel waveguides **21** and at least one output channel waveguide **22**. The light emitted from each emitter **18** is received by one of the input channel waveguide **21**, and then wavelength combined by the AWG **19**. Each of the input channel waveguides **21** is provided with Bragg grating **23** written into a portion of the input channel waveguide **21**. The Bragg gratings can be formed holographically, by exposing a germanium-containing fiber to ultraviolet light through a phase mask. The Bragg grating **23** is adapted for a predetermined wavelength called center wavelength, λ_i , of the grating **23**, providing optical feedback to the light emitter **18**, and locking the axial mode wavelength of the light emitter **18** to the center wavelength of the grating **23**. In the present embodiment, the number of the light emitters of the laser diode array **17** is as the same as the number of the input channel waveguides of the AWG **19**.

In the pump light laser source, the input channel waveguides are adopted for a plurality of wavelengths ($\lambda_1, \lambda_2, \dots, \lambda_i, \dots, \lambda_n$), being within the bandwidth of the said light emitter of the laser diode array **17**. In the present embodiment, the wavelength spacing between the input channel waveguide, $\Delta\lambda_i = \lambda_i - \lambda_{i-1}$, is substantially constant, and is about 0.4 nm. As the wavelength from each emitter is locked by a Fiber Bragg Grating (FBG) or the Bragg grating on the input channel waveguide, stability of the present proposed laser diode is maintained. In addition, since spectrum width of the laser is determined by the FBG, the total spectrum width can be preset at a small value.

The number of the light emitters of the said laser diode array can be readily increased in accordance with the requirements for industry applications. A high

power output can be easily obtained through the wavelength combination of the light power from all emitters using AWG based WDM coupler.

Due to the divergent emission effect **25** of the light at the aperture **26** of the gain medium **27** in the laser light emitter, as shown in **Fig. 3**, the coupling between the light emitters of the laser diode array **17** and the input channel waveguides of the said AWG **19** can be inefficient. The gain medium **27** in the laser light emitter is typically made of InGaAsP. Referring now to **FIG. 4**, in order to improve such coupling efficiency the pump light laser apparatus can further comprises a plurality of optical lens array **30** held by the lens array support **31**, and disposed between the said laser diode array **17** and the input channel waveguides of the AWG **19** for collimating the light emitted from the light emitters. Alternatively, the aperture of the laser diode can be tapered to form a spot-size converter to match the mode field of the input channel waveguide of the said AWG **19**. The spot-size converter **32** can be formed by an outwardly divergent portion of the gain medium of the light emitter, as shown in **Fig. 5 (a)**, or by an inwardly convergent portion of the gain medium of the light emitter, as shown in **Fig. 5 (b)**. This structure enhances the coupling efficiency between laser diode array and the AWG type WDM coupler, and can further increase the light power output.

Although the present invention has been described with reference to the preferred embodiment, it is apparent to those who are skilled in the art to recognize that changes and modifications may be made in form and detail without departing from the spirit and scope of the invention as defined in the following claims.

CLAIMS

What is claimed is:

1. A pump light laser apparatus comprising:
 - a laser diode array having a plurality of light emitters;
 - an arrayed waveguide grating (AWG) provided on a substrate, having a plurality of input channel waveguides to receive the light emitted from the said light emitters, and at least one output channel waveguide;
 - wherein each of the said input channel waveguides being provided with Bragg grating means adapted for a predetermined wavelength, having Bragg grating written into a portion of the said input channel waveguides; said grating having a center wavelength, providing optical feedback to said light source, and locking the axial mode wavelength of the light emitter to the center wavelength of the grating;
 - wherein the said input channel waveguides are adopted for a plurality of wavelengths ($\lambda_1, \lambda_2, \dots, \lambda_i, \dots, \lambda_n$),, being within the bandwidth of the said light emitter of the laser diode array, and wherein the wavelength spacing between the input channel waveguide, $\Delta\lambda_i = \lambda_i - \lambda_{i-1}$, is substantially constant.
2. The pump light laser apparatus of claim 1, wherein the wavelength spacing between the input channel waveguide is about 0.4 nm.
3. A pump light laser apparatus as claimed in claim 1, further comprises a plurality of optical lens array disposed between the said laser diode array and the input channel waveguides for collimating the light emitted from the light emitters.
4. A pump light laser apparatus as claimed in claim 1, wherein the aperture of the laser diode is tapered to match the mode field of the input channel waveguide of the said AWG.