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OSA CONTINUUM

Resonant pumping of high power fiber lasers with conventional laser diodes

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Abstract: We demonstrate a very simple and impactful scheme based on parallel electrical relay control of conventional diodes without wavelength locking for the resonant pumping of high power fiber lasers. This scheme enhances the efficiency and reduces the thermal load on the laser. The deleterious effects due to drift in emission wavelength of the diodes from the peak absorption of the gain medium with varying output power is avoided. We also demonstrate that the proposed technique performs comparably with pumping with wavelength locked laser diodes.

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1. Introduction

Laser diodes have become the most preferred choice for optical pumping in fiber lasers. With the strained semiconductor fabrication technology, several hundred watts of CW power at desired wavelengths can be generated from a packaged, single laser diode module. And output from several such laser diode modules could be then combined together, to pump fiber lasers enabling output powers of several kW.

For pumping of rare-earth doped fiber lasers and amplifiers, it is crucial to ensure maximum overlap between the pump laser diode emission wavelength with the peak absorption wavelength of the gain medium [1]. This enables the optimal balance of cost, nonlinearities such as stimulated Raman and Brillouin scattering and laser efficiency [1–3]. However even with utmost care in choosing the right laser diode with appropriate emission profile, it is quite difficult to ensure the above-mentioned overlap condition because of the dependence of the emission wavelength on the diode with drive current. The conventional and widely utilized scheme for driving the diodes is having them in series. Output power tuning from the laser is achieved by changing the drive current to the diodes. However, this results in a drift in the emission wavelength of the diodes with changing current. This can detrimentally affect the efficiency and stability of the laser system and also result in an increased thermal load on cladding mode stripper. For example, in Ytterbium (Yb) doped fiber lasers, a change in pumping wavelength by 5nm around the resonant wavelength can cause a reduction in magnitude of pump absorption per unit length (in log scale units) by >50%. This issue becomes crucial in high power lasers where the thermal load on the system has to be maintained low in order to ensure better beam quality [4] and also to avoid output wavelength fluctuation due to thermal instability [5]. Arbitrary enhancement of gain medium length is impractical in terms of cost and nonlinearity.

2. Experiment

We first demonstrate through an experiment, the drift of the pump wavelength with power tuning (diode current tuning) in the case of conventional diode drive scheme and look at its influence on unabsorbed pump power. In our experiment, ‘6’ numbers of nominally 10 W diodes (JDSU L4t) with an output wavelength of 977 nm at full power (12A of drive current), operating at a constant temperature of 25 C (water cooled) is used. Figure 1(a) shows the absorption spectra of 10m length of double clad Yb-doped fiber (Nufern SM-YDF-5-130)

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OSA CONTINUUM

with a total peak absorption of ~17dB. From Fig. 1(b) it is clear the emission wavelengths of all diodes at full power was reasonably matched to the Yb-absorption band. However it is also evident that there is a significant mismatch between the same at lower power levels (current levels). We observed as specified in the specification sheet, a ~1nm/A drift in wavelength with drive current. But the functionality of a laser system demands operation at varying power levels and it is not only difficult but also important to handle the unabsorbed pump power that comes out at the end of the gain fiber as a consequence of this wavelength drift, especially for high power fiber lasers.

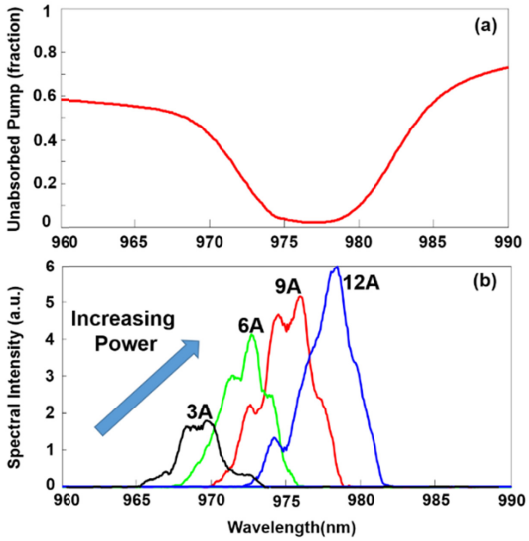

Fig. 1. (a) Fraction of Unabsorbed pump power in 10m of Yb-doped double clad fiber with a net peak absorption of ~17dB (b) Variation of pump laser wavelength as the power is increased (change in drive current).

Currently, this is achieved through the use of wavelength locked laser diodes. Wavelength locking is achieved through the use of volume Bragg gratings inside the diode package. However, this comes at the cost of enhanced cost and reduced efficiency of the diode modules. Even with these added considerations, currently available high power wavelength locked diodes do have limitations such as lack of an ability to emit the correct wavelength at lower power levels (drive currents). Here, we propose a simple drive scheme for conventional laser diodes, which enables resonant pumping, and all the associated advantages without the disadvantages of using wavelength locked laser diode modules.

2.1 Modified drive scheme

The wavelength of conventional laser diodes vary with drive current, and temperature. The emission wavelength at full power is also a function of process parameters. The temperature variation can be handled by the heat-sink temperature and process variations between diodes can be taken care of by binning diodes such that all diodes utilized for a specific laser system have the same output wavelength at full power. The primary problem that needs to be addressed is the wavelength drift with changing drive current (necessary for power tuning).

In our scheme, we utilize the fact that high power laser systems constitute a multitude of laser diodes (a kW laser module can utilize 10s of laser diode modules) and alternate means of power tuning without changing the drive current can be found due to the numbers. The starting point is to use a set of binned diodes, which have the same output wavelength at full current and then adjusting the heat-sink temperature to ensure at full power, the emission wavelength matches the peak absorption wavelength of the gain medium. Now, by

OSA CONTINUUM

individually turning on a subset or all diodes in the laser at full current, power tuning can be achieved while simultaneously ensuring the right emission wavelength for each.

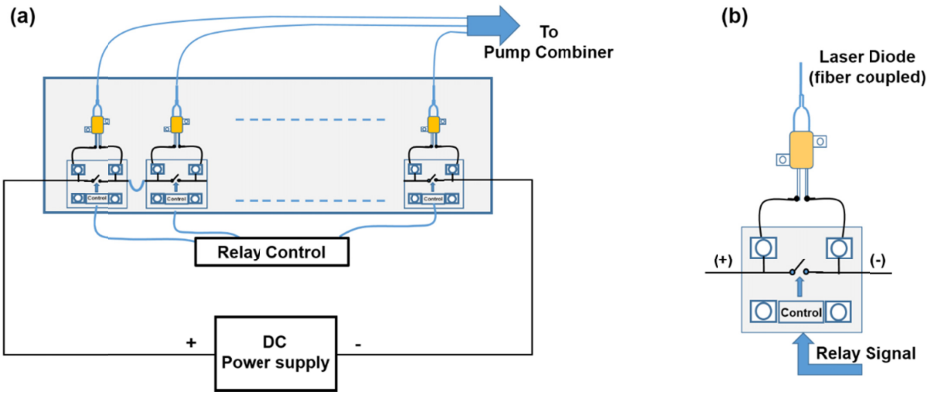

Fig. 2. (a) Schematic of the modified diode drive scheme. (b) Schematic for the laser diode-relay connection.

Figure 2(a) shows the experimental setup to achieve this and Fig. 2(b) represents the schematic for the laser diode-relay connection (here the switching is performed using computer controlled solid state relays). Inexpensive solid state relays (Crydom, D1D20, 20A, 100V, DC-DC relay) are connected in parallel to each diode module. The relays are chosen such that the ON state resistance is low enough that the threshold for emission is not achieved in the parallel path containing the diodes in this state. Initially, all relays are in an ON state, the DC power supply is set at the appropriate current level (in our case 12A, the maximum) and the heat-sink temperature is adjusted appropriately (in our case 25C). The relays are computer controlled using a digital I/O board.

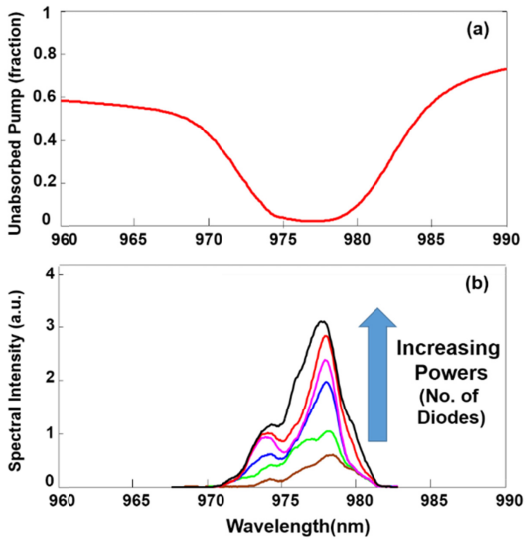

Fig. 3. (a) Fraction of Unabsorbed pump power in Yb-doped double clad fiber with a peak total absorption of ~17dB (b) Variation of pump laser wavelength as the power is increased (change in diode number).

As shown in Fig. 3, when the individual relays are turned OFF, individual diodes turn-on directly at resonance. In contrast to the conventional scheme (Fig. 1), power tuning is achieved at resonance. The resolution for output power tuning is determined by the reciprocal

OSA CONTINUUM

of number of pump diodes used and practical systems will have several 10's of such pump diodes, which provides sufficient steps for fine tuning of power. Figure 4 shows the unabsorbed pump power with the conventional drive scheme, modified drive scheme and the optimal value for a length of Yb-doped fiber with a peak absorption of ~17-dB. As a consequence of the wavelength drift, in conventional diode drive scheme there is reduced absorption of pump power especially at lower power range where there is significant mismatch between the emission wavelength and absorption peak of the gain medium. With the modified diode drive scheme that we propose, the magnitude of pump absorption is constant over the entire power tuning range and very close to the best value possible. This was achieved since we turned on the diodes only at the maximum drive current (at 12A) where they operate at the wavelength corresponding to the best absorption band of the gain medium.

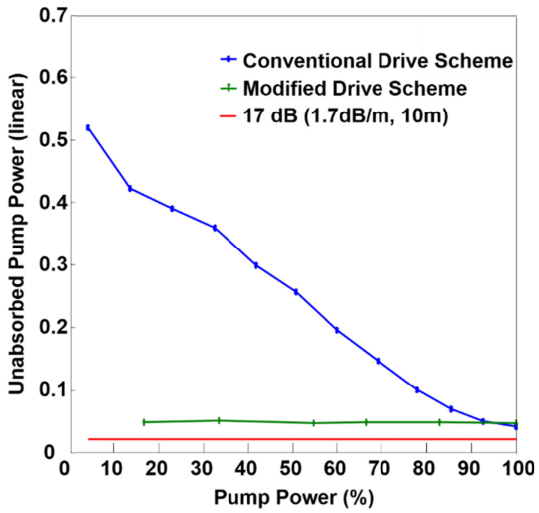

Fig. 4. Comparison of unabsorbed pump fraction in a length of Yb-doped fiber with a peak total absorption of 17dB for different schemes.

The magnitude of pump absorption is one of the key factors influencing the efficiency of the laser system and the thermal load on the cladding mode stripper (also referred to as a pump-dump) [6]. We see a significant enhancement in the fraction of pump power absorbed over the entire power range for the modified drive scheme with an unabsorbed pump level of ~4% in comparison to the optimal value of 2%. This small deviation from the optimal value is due to the finite bandwidth of the laser diodes which can be compensated by a slightly increasing the length of the gain fiber.

An important issue to consider is potential degradation of the laser diode modules due to the modified drive scheme. However, due to the relatively slow response time of the relay-DC power source circuit, being > 200 milliseconds, no degradation of the laser diode modules were observed over more than 100 On-OFF power cycling experiments. The response however is fast enough that the transient in output wavelength before the final wavelength is reached does not cause thermal issues. Also, an internal counter is maintained for each laser diode, within the code. This ensures that the number of turn ON/OFF cycle for each laser diode is nearly the same during multiple operations.

OSA CONTINUUM

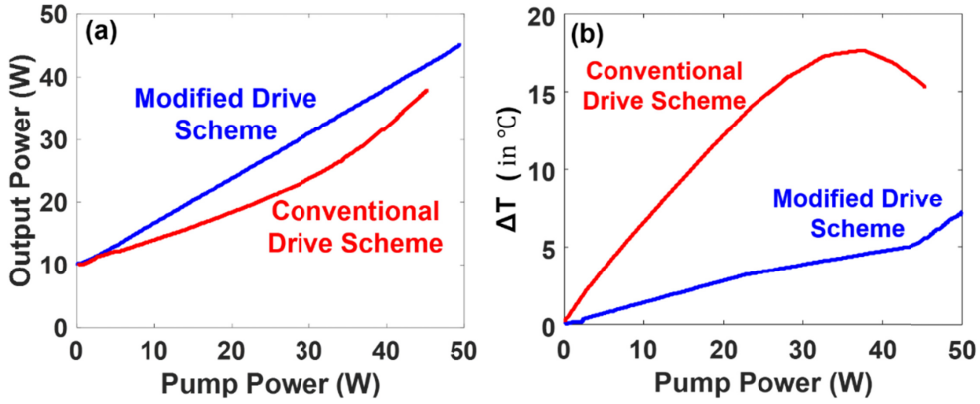

Fig. 5. (a) Plot comparing output power vs. input power in an amplifier configuration for the two drive schemes (b) Plot showing temperature rise of the cladding power stripper for the two drive schemes.

A more representative experiment to characterize the benefits of the modified diode drive scheme is in a laser configuration. A Yb doped fiber amplifier with nominally 17-dB of small signal pump absorption (10m of Yb-doped double clad fiber (Nufern SM-YDF-5-130) with a peak cladding absorption of 1.7dB/m), ~10W of input power at 1064nm (from a ring laser seed) and pumped by '6' nominally 10W laser diodes was constructed. Figure 5(a) shows the output power from the amplifier (interpolated between data points) as a function of pump power for the conventional and the modified drive schemes. As expected in the efficiency plot, for the conventional drive scheme, a nonlinear behavior is observed due to the progressive reaching of peak absorption by the diodes with power. In contrast, with the modified drive scheme, the amplifier performance is linear across the power range with enhanced efficiency in the intermediate power levels. Figure 5(b) (interpolated between data points) shows the temperature increase of the cladding mode stripper (constituted of coating stripped region with high-index thermal paste). This is a crucial measure for reliability of the laser system. With the modified drive scheme, since the thermal load on the pump dump region is substantially lower across the power range, much lower, linear temperature raise was observed. From Fig. 5(b), we can conclude that assuming a threshold value of temperature for failure, the modified drive scheme can handle three times as much power.

3. Comparison

Currently, for diode emission spectrum at fixed wavelength for all power levels, laser diodes with volume Bragg grating (VBG), also known as wavelength locked diodes are used. However, the extra optical components along with external cavity in these laser diodes further add cost and losses thereby reducing the wall-plug efficiency of the laser system. Here, we try to compare the performance of pumping done using wavelength locked diodes vs. conventional laser diodes with the proposed modified drive scheme. This comparison is important because, in wavelength locked diodes, in addition to the locking of center wavelength, the bandwidth is substantially narrowed as well (<0.5nm) while in the proposed scheme, the bandwidth is unchanged (3-5nm, depending on the module).

OSA CONTINUUM

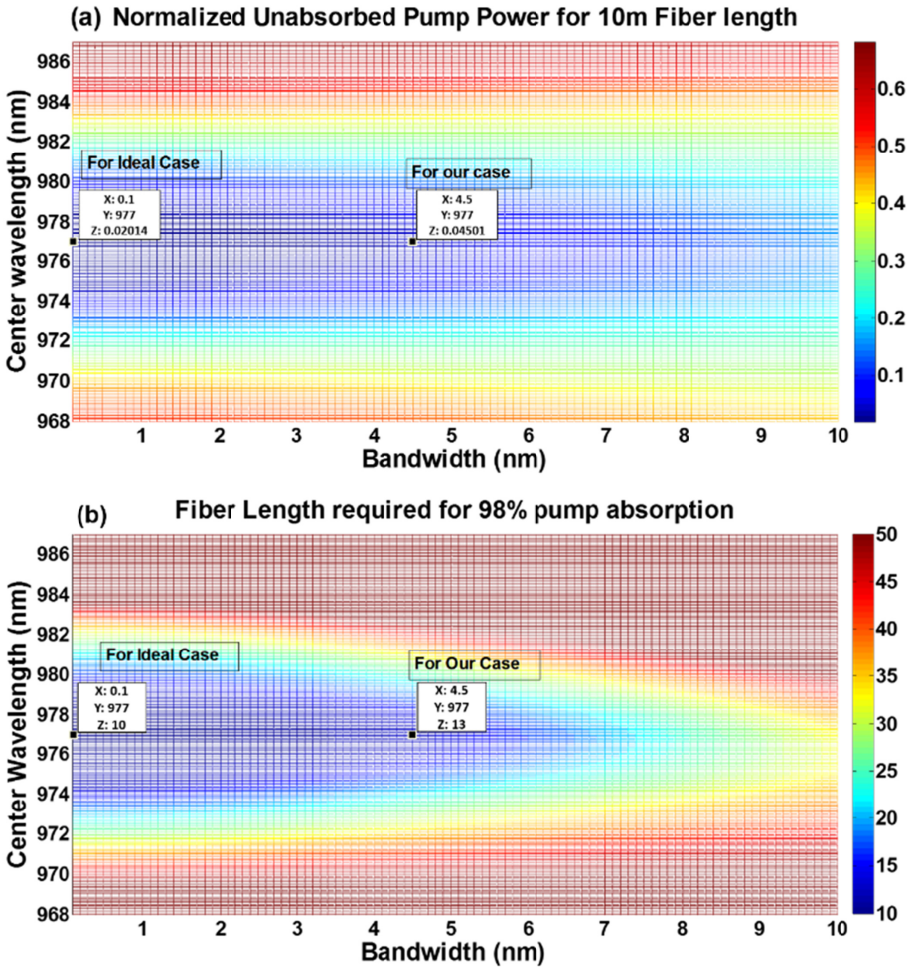

Fig. 6. (a) Plot showing the magnitude of unabsorbed pump power with variation in bandwidth and center wavelength in a medium with 17dB of peak absorption (10m of 1.7dB/m) (b) Plot showing the length of active fiber required(in meters) for different values of center wavelength and bandwidth.

The actual efficiency is specific to the laser architecture varying based on multiple parameters such as resonator design in the case of an oscillator, seeding power in the case of an amplifier, emission wavelength and additional losses. Here, to capture the aspects related only to the pump diode wavelength, we are using the difference in small signal pump absorption as a representative. This is a good measure for high power lasers and amplifiers, which operate in the gain saturation regime. Figure 6(a) shows a comparison between the magnitude of pump absorption with variation in center wavelength and bandwidth. The difference in pump absorption while pumping a 10m long active double clad fiber with a net absorption of ~1.7dB/m and total absorption of ~17dB is shown. For the wavelength locked diode, a strict impulse spectrum at the peak absorption wavelength is assumed. For the conventional case, the spectrum measured in our experiments is used. As shown in the figure, the effect of bandwidth of the pump diode has a smaller impact compared to the shift in center wavelength. This is due to the natural linewidth that exists for the gain media, which in the case of Ytterbium is comparable to the diode emission bandwidth. The two points shown, one for the ideal case and the other for modified drive case show only 2% difference in the amount of unabsorbed power. A better representation of this data is to evaluate the additional

OSA CONTINUUM

length of the gain media necessary to achieve the same level of pump absorption as the ideal case. This captures the consequences of additional nonlinear effects and cost considerations of the modified scheme. To achieve 98% of net absorption (17dB), 10m of fiber is necessary with wavelength locked diodes and 13m of fiber is necessary with the modified drive scheme. This is a relatively small overhead of 30%. Figure 6(b) shows how the length of active fiber required varies with change in center wavelength and bandwidth. It is evident from this plot that the margin of superiority that the wavelength locked laser diodes has in terms of linewidth and spectral purity over the conventional diodes doesn't result in substantial difference to reliable and efficient functioning of the laser system if its operated using the modified drive scheme. In addition, the use of the broader bandwidth conventional laser diodes enables a more gradual absorption over fiber length compared to wavelength locked diodes. This has been observed to be beneficial with respect to heating of the fiber due to thermal load. It is also useful in the case of high gain, high power amplifiers, where, due to low input signal power, inversion saturation is likely in the case of wavelength locked diodes due to higher absorption cross-sections.

It is essential to note that, the proposed scheme utilized the multitude of pump laser modules in the laser system to obtain better performance as the number of modules increases. This is thus more applicable to systems of high average power. For amplifiers, which have low average power, but high nonlinearity, such as short pulse amplifiers, wavelength locked laser diodes are still essential and the proposed technique does not work in such cases.

4. Summary

We have demonstrated a very simple, reliable diode drive scheme for conventional pump laser diodes that makes diode pumped fiber laser systems immune to the deleterious effects associated with drift in emission wavelength during power/current tuning. We have shown that this technique can significantly improve the efficiency and thermal performance of lasers over the entire range of power tuning. Also, we demonstrated that the performance is almost similar to wavelength locked laser diodes without the added cost or efficiency reduction. We believe utilization of this technique will enable substantial performance improvements in fiber laser systems, particularly nonlinearity constrained systems such as narrow-linewidth fiber lasers and very high average power fiber lasers.

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