Study on Influence of Pumping Spectrum on Stable Uniform Pumping in a Side-Pumped Nd:YAG Amplifier

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Abstract: A new method to realize temperature-stable uniform pumping was presented. Concept of effective absorption coefficient is introduced at first, which is used to indicate actual absorption coefficient of Nd:YAG working materials that concerned the influence of laser diode pumping spectrum characters. After this, flattop and Gaussian as a typical pumping spectrum shaping are discussed, and experimental measured laser diode spectrum is also used to calculate effective absorption coefficient as a comparison. Next, experimental results of pump laser diode deviating from absorption peak of neodymium ion are also numerical analysed, and these results are used to guide pumping central wavelength control. Finally, an optimized laser diode pumping spectrum shape is put forward. With such a pumping spectrum shape, effective absorption spectrum can be optimized to flattop shape, and temperature-stable uniform pumping can be realized.

1 INTRODUCTION

Laser pulses with flattop energy distribution are known to present significant advantages for laser machining and various nonlinear optical processes (Shealy and Chao, 2004). To amplify signal laser with a flattop energy distribution, a uniform spatial pumping profile can improve population inversion in laser amplifiers, reduce thermally induced stress birefringence, and diminish depolarization loss (Mashaiekhyasl 2012, Park et al. 2006, Kojima et al. 1999). Flattop pumping energy distribution has been performed by a variety of means to realize this, including uniformly arrange laser diodes and optimize structural parameters (Kotlyar et al. 2008, Borghi 2013), or using special optical elements such as waveguide, diffuse-reflective cavity or hollow duct (Taghizadeh et al. 2000, Baker et al. 2009, Zhao et al. 2012). However, spectrum is another important associated factor shall be considered to realize uniform spatial pumping profile. As we know, absorption peaks of Nd:YAG are centered at 808.6 nm, and the FWHM (full width at half maximum) of absorption coefficient is less than 2 nm (Kaufman & Oppenheim 1974). If central wavelength of the pump light seriously deviated from absorption peak, pumping energy distribution would change obviously, and this would induce serious gain distribution inconformity on cross-section of the working material. Hence, it is generally important to maintain stable spectrum characters of the pump light to obtain high beam quality, minor distortion and high transmission accuracy laser. As far as we know, there is few report about the spectrum optimization of the pump light to gain stable uniform pumping in a side-pump amplifier.

Uniform extraction of flattop beams from side-pumped laser rods in amplifiers suffers from the trade off of gain distribution stability and pump efficiency caused by pump spectrum bandwidth. If pump spectrum bandwidth was too small, deviation of central pump wavelength would obviously decrease pumping efficiency, and deteriorate pump uniformity. On the contrary, if pump bandwidth was too large, pump efficiency would be too low, although environmental suitability would be better. In this paper, concept of effective absorption spectrum is put forward, which is used to analysis the amplification system that pumping spectrum of laser diodes should be carefully considered. Here, effects of pumping spectrum bandwidth and specific shape are calculated. Further, relations between spectrum of the pump light and stability of pump

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energy distribution are discussed. Influences of central wavelength of the pump light deviate from absorption peak of Nd:YAG are analysed. By simulative and experimental results, optimized pump spectrum shape is put forward, and a proper temperature-stable uniform pumping method is presented.

2 ABSORPTION SPECTRUM AND EFFECTIVE ABSORPTION SPECTRUM

To realize a precisely absorption spectrum measurement, a 2.5mm thickness slab is taken from the same crystal ingots of the Nd:YAG rod that used in the amplifier. Optical absorption coefficient measurements were carried out by using an ANDO AQ-6315A optical spectrum analyzer and an ANDO AQ-4303B white-light source. Absorption coefficient α can be expressed as

$$\alpha = -\frac{1}{L}\ln\left(\frac{I}{I_0}\left[1-\left(\frac{n_1-n_0}{n_1+n_0}\right)^2\right]^{-2}\right) \quad (1)$$

Where, I_0 is the incident light power, I is the transmitted light power, L is the thickness of the slice, n_1 is the refractive index of the Nd:YAG slice, n_0 is the refractive index of air. Experimental results indicate that n_1 is 1.822, and Fresnel loss on the refractive surface is 8.49%. In this way, average absorption spectra from 800nm to 820nm can be calculated, and the results are shown in Table 1.

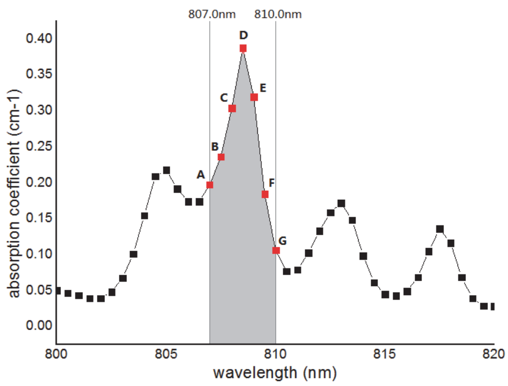

Figure 1: Measuring result about absorption coefficient of the Nd:YAG rod in experimental.

As we know, atoms rise from the ground state [4]I9/2 to the state [4]F5/2 induces a series of absorption peaks. 808.6nm are always regarded as the central wavelength for pumping. But spectrum width and other absorption peaks (such as 804.5nm or 814.0nm) also have influences on absorption efficiency. High power laser diode arrays typically have a spectral full width at half maximum (FWHM) of 3~5 nm, and this will influence absorption obviously. For example, when the central wavelength is 808.5nm, and pumping spectrum width is 3nm, it means that a region from 807.0nm to 810.0nm will be covered. As shown in Fig.1, each point in the effective region

Table 1: Measuring result of I/I_0 and absorption coefficient of the Nd:YAG rod in experimental.

Wavelength (nm)	I/I_0 (a.u.)	absorption coefficient (mm^{-1})
820.0	0.2188	0.0278
819.5	0.2203	0.0286
819.0	0.2408	0.0392
818.5	0.2941	0.0684
818.0	0.3736	0.1161
817.5	0.4035	0.1357
817.0	0.3553	0.1046
816.5	0.2945	0.0685
816.0	0.2592	0.0490
815.5	0.2471	0.0426
815.0	0.2513	0.0448
814.5	0.2811	0.0610
814.0	0.3453	0.0985
813.5	0.4214	0.1479
813.0	0.4551	0.1719
812.5	0.4365	0.1584
812.0	0.3989	0.1326
811.5	0.3515	0.1023
811.0	0.3123	0.0788
810.5	0.3093	0.0770
810.0	0.3575	0.1060
809.5	0.4717	0.1842
809.0	0.6231	0.3194
808.5	0.6821	0.3874
808.0	0.6083	0.3039
807.5	0.5362	0.2364
807.0	0.4889	0.1975
806.5	0.4578	0.1739
806.0	0.4580	0.1740
805.5	0.4813	0.1916
805.0	0.5140	0.2177
804.5	0.5034	0.2090
804.0	0.4308	0.1544
803.5	0.3495	0.1010
803.0	0.2925	0.0674
802.5	0.2576	0.0482
802.0	0.2408	0.0392
801.5	0.2403	0.0390
801.0	0.2483	0.0432
800.5	0.2544	0.0465
800.0	0.2617	0.0504

has different contribution to absorption. In this paper, we regard the absorption spectrum which considering pumping spectrum width of laser diode as the effective absorption spectrum.

3 CHARACTERS ABOUT EFFECTIVE ABSORPTION SPECTRUM

If regarded the spectrum of the pumping light as an ideal flattop distribution, each point will has the same contribution to absorption. Effective absorption coefficient can be calculated from the geometric averages

$$\alpha_{eff} = \frac{1}{n}\sum_{i=1}^{n}\alpha_i \qquad (2)$$

Where, α_i is the absorption coefficient on effective points, α_{eff} is the effective absorption coefficient, n is the number of effective points. If interval between two sampling point is 0.5nm, $n = 2d + 1$, d is the FWHM of pumping spectrum. In Fig.1, absorption coefficient of point A (807.0nm) is 0.1975/mm, B (807.5nm) is 0.2364/mm, C (808.0nm) is 0.3039/mm, D (808.5nm) is 0.3874/mm, E (809.0nm) is 0.3194/mm, F (809.5nm) is 0.1842/mm, and G (810.0nm) is 0.1060/mm. Therefore, for the case of 3nm spectrum width from 807.0nm to 810.0nm, α_{eff} is 0.2478/mm.

In most cases, the pumping spectrum is similar to Gaussian distribution. That means each point will have a contribution coefficient. If regarded the pumping spectrum as an ideal Gaussian distribution, then

$$f(x) = \exp\left(-\frac{x^2}{2c^2}\right) \qquad (3)$$

and FWHM

$$d = 2\sqrt{2\ln 2}c = 2.3548c \qquad (4)$$

If interval between two sampling point is 0.5nm, and contribution coefficient of central wavelength point is normalized as 1, contribution coefficient of others points can be calculated. To the situation of d is 1nm, 3nm, 6nm, and 10nm, if regards central wavelength point as the origin, contribution coefficient on positive axis can be calculated. Contribution coefficients lower than 0.01 are ignored.

Effective absorption coefficient can be calculated as following

$$\alpha_{eff} = \sum \frac{c_i}{\sum c_i}\alpha_i \qquad (5)$$

Where, c_i is the contribution coefficient on each effective point. To the situation of flattop distribution and Gaussian distribution, effective absorption spectrums are plotted in Fig.2 and Fig.3.

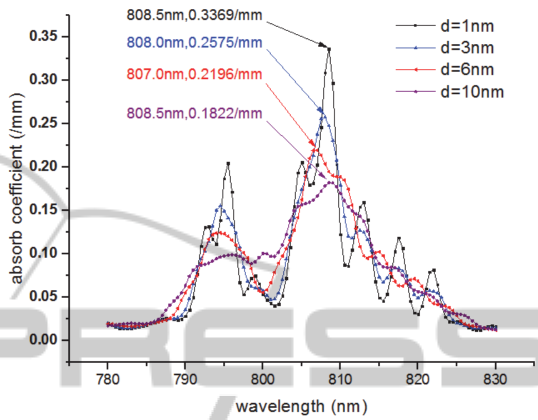

Figure 2: Effective absorption coefficient of flattop distribution pumping spectrum with FWHM=1, 3, 6, 10nm.

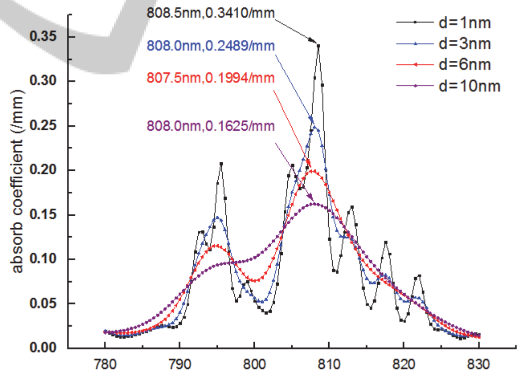

Figure 3: Effective absorption coefficient of Gaussian distribution pumping spectrum with FWHM=1, 3, 6, 10nm.

These two figures show that: If d is smaller, effective absorption spectrum is more similar to Nd:YAG absorption spectrum. In most cases, if d is smaller than 1nm, effective absorption spectrum can be regarded similar as absorption spectrum, but peak point of effective absorption coefficient drops obviously. Such as to the situation of Gaussian-distribution pumping spectrum, effective absorption coefficient on 808.5nm is 0.3410/mm (d =1nm), but peak point of actual absorption coefficient 0.3874/mm, there is a 12% decrease.

If d is over 3nm, effective absorption spectrum will be obviously reshaped. Peak point of the effective absorption spectrum is deviated from the absorb spectrum center. In Fig.2, to the situation of d =1nm, 3nm, 6nm, 10nm, peak point of the effective absorption spectrum is 808.5nm (0.3369/mm), 808.0nm (0.2575/mm), 807.0nm (0.2196/mm), 808.5nm (0.1822/mm). In Fig.3, peak point of the effective absorption spectrum is 808.5nm (0.3410/mm), 808.0nm (0.2489/mm), 807.5nm (0.1994/mm), 808.0nm (0.1625/mm). That means wider pumping spectrum will induce lower peak point of effective absorption coefficient, and this is obvious in the situation of narrow pumping spectrum. If regards peak effective absorption coefficient of FWHM=1nm as 100%(808.5nm, 0.3410/mm), it would be 83.0% (FWHM=2nm, 808.5nm, 0.2831/mm), 73.0%(FWHM=3nm, 808.0nm, 0.2489/mm), 66.8%(FWHM=4nm, 808.0nm, 0.2277/mm), 62.3%(FWHM=5nm, 807.5nm, 0.2124/mm), (FWHM=6nm, 807.5nm, 0.1994/mm), 52.3%(FWHM=8nm, 808.5nm, 0.1785/mm), 47.7%(FWHM=10nm, 808.5nm, 0.1625/mm).

When d is enlarged from 1 to 10nm, effective uniform region of effective absorption coefficient is enlarged. To the situation of flattop distribution, and d =1nm, 3nm, 6nm, 10nm, width of 80% peak point of effective absorption coefficient is 1.0nm (808.0~809.0nm), 3.0nm (806.5~809.5nm), 6.0nm (805.5~810.5nm), 8.0nm (804.0~812.0nm), respectively. To the situation of Gaussian distribution, width of 80% peak point of effective absorption coefficient is 1.0nm (808.0~809.0nm), 3.5nm (806.0~809.5nm), 5.5nm (805.0~810.5nm), 9nm (803.5~812.5nm), respectively. Making a contrast between Fig.2 and Fig.3, 80% peak point width of Gaussian and flattop distribution is similar. While, if regard 90% peak point of effective absorption coefficient as a kind of uniform standard, to the situation of flattop distribution, d =1nm, 3nm, 6nm, 10nm, width of 90% peak point of effective absorption coefficient is <1.0nm (808.5nm one point), 1.5nm (807.0~808.5nm), 2.0nm (806.0~808.0nm), 3.0nm (807.0~810.0nm), respectively. To the situation of Gaussian distribution, width of 90% peak point of effective absorption coefficient is <1.0nm (808.5nm one point), 2.0nm (807.0~809.0nm), 3.5nm (806.0~809.5nm), 6.0nm (805.0~811.0nm), respectively. It should be pointed out that absorb spectrum measuring precision is 0.5nm.

Thus it can be seen that pumping spectrum distribution has obvious impact on global shape of pumping. The best way to decrease error from pumping spectrum shape is getting the pumping spectrum data by experiment.

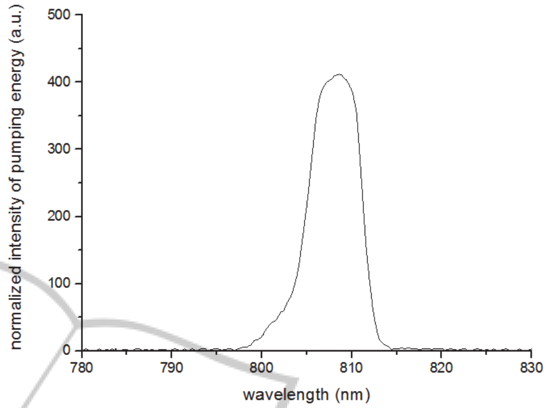

Figure 4: Measurement result of pumping spectrum to the side-pumping amplifier.

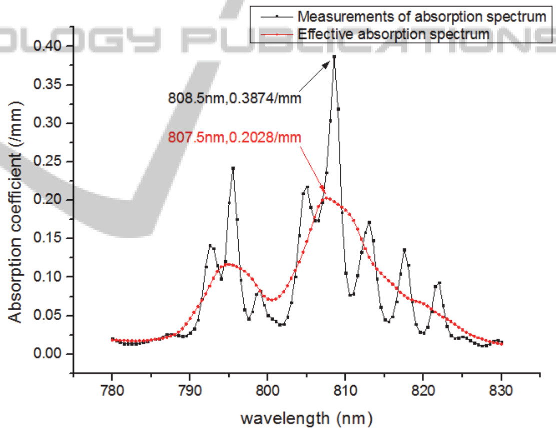

Figure 5: Effective absorption spectrum calculated from experimental pumping spectrum.

The experimental scheme of the pumping spectrum measurement contains three parts which are the side-pumped amplifier, focusing lens, and spectrometer. Focal length of the lens is 150mm, and diameter is 25.4mm. The distance between the amplifier and focusing lens is 910mm. Model of the spectrometer is AVaSpec-3648 (Avantes Co. Ltd), and it is placed on focusing point of the lens. A piece of optical filter, which can absorb 1064nm, and let 808nm laser transmit is used in front of the receiver of the spectrometer. Absorption spectrum measurements result is shown in Fig.4. It is a typical pumping spectrum, and FWHM of the pumping spectrum is 6.3nm. By the same calculation method, effective absorb coefficient is distributed to each points, and effective absorb spectrum is plotted in Fig.5. The shape of effective absorption spectrum calculated from measurements result of pumping spectrum is an intermediate state between Fig.2 and Fig.3. Peak point is 0.2028/mm, and the central wavelength is 807.5nm. Range of 80% peak point is 5.5nm (from 806.0nm to 811.5nm), and range of 90% peak point is 3.5nm (from 806.5nm to 810.0nm).

Table 2: Contrasting between effective absorption coefficients with different pumping spectrum distributions.

Wavelength (nm)	α_{eff}-F (mm^{-1})	α_{eff}-G (mm^{-1})	α_{eff}-E (mm^{-1})
820.0	0.0687	0.0601	0.0656
819.5	0.0712	0.0629	0.0676
819.0	0.07	0.0658	0.0689
818.5	0.0661	0.0686	0.0704
818.0	0.0628	0.0715	0.0728
817.5	0.0632	0.0745	0.0762
817.0	0.0681	0.0776	0.0807
816.5	0.0773	0.0810	0.0859
816.0	0.0883	0.0848	0.0911
815.5	0.0975	0.0889	0.0957
815.0	0.1024	0.0937	0.1003
814.5	0.1014	0.0990	0.1054
814.0	0.097	0.1050	0.1107
813.5	0.0949	0.1117	0.1173
813.0	0.0977	0.1192	0.1261
812.5	0.1081	0.1274	0.1372
812.0	0.1294	0.1363	0.1498
811.5	0.1558	0.1459	0.1627
811.0	0.1745	0.1558	0.1738
810.5	0.1851	0.1658	0.1819
810.0	0.1889	0.1754	0.1872
809.5	0.1891	0.1841	0.1911
809.0	0.1903	0.1913	0.1946
808.5	0.1948	0.1966	0.1983
808.0	0.2037	0.1994	0.2014
807.5	0.2137	0.1994	0.2028
807.0	0.2196	0.1967	0.2002
806.5	0.2193	0.1913	0.1918
806.0	0.2103	0.1835	0.1781
805.5	0.1894	0.1736	0.1622
805.0	0.1626	0.1622	0.1466
804.5	0.1422	0.1499	0.1324
804.0	0.1274	0.1371	0.1199
803.5	0.1158	0.1244	0.1088
803.0	0.1063	0.1125	0.0987
802.5	0.0978	0.1017	0.0891
802.0	0.0894	0.0925	0.0809
801.5	0.0787	0.0852	0.0753
801.0	0.0669	0.0800	0.0717
800.5	0.0586	0.0769	0.0701
800.0	0.0553	0.0759	0.0714

Table 2 makes a contrast about effective absorption coefficient among three different situations. α_{eff} -F is the effective absorption coefficient with flattop distribution pumping spectrum and FWHM=6nm. α_{eff}-G is the effective absorption coefficient with Gaussian distribution pumping spectrum and FWHM=6nm. α_{eff}-E is the effective absorption coefficient with experimental LD pumping spectrum and FWHM=6.3nm.

4 INFLUENCE OF EFFECTIVE ABSORPTION COEFFICIENT ON UNIFORM PUMPING

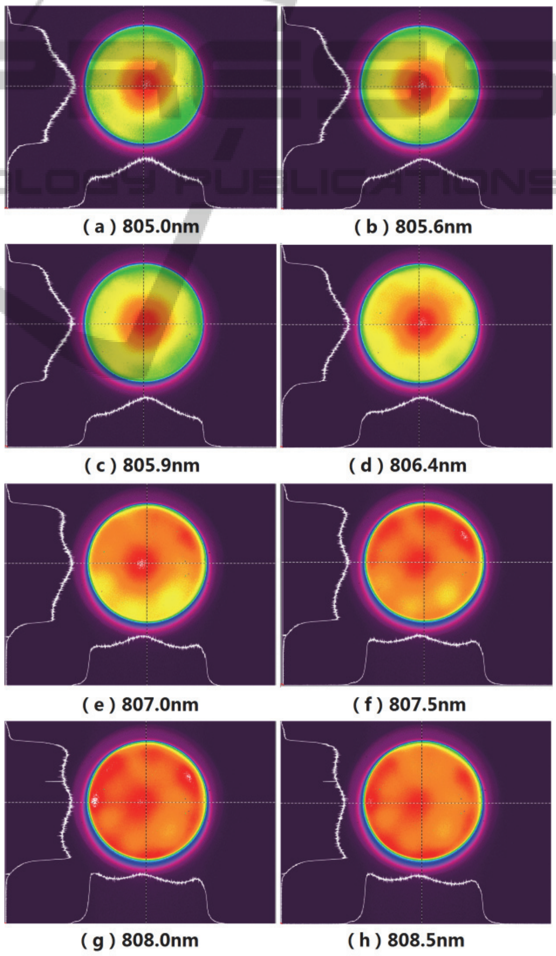

Figure 6: Influence of central wavelength of pumping spectrum on pumping energy distribution.

Measurement scheme of pumping energy distribution is similar to pumping spectrum, but only a silicon CCD camera (SP620U, Ophir Co. Ltd.) is used to substitute spectrometer. In the amplifier, 7 laser diode arrays are placed around the working material in circle, and fast axis is paralleled with the rod. The fluorescence distribution images of central pumping wavelength from 805.0nm to 808.5nm are shown in Fig.6. Experimental results illuminate that central pumping wavelength has effected fluorescence distribution obviously. When central pumping wavelength increasing, fluorescence density in the centre of the rod drops obviously.

After converse measuring results in Fig.6 to grayscale, normalized fluorescence density on horizontal and vertical cross-section are presented. Making a contrast between gray level of central point and average of the four edge points, sketchy quantitative analysis results can be gained. From 805.0nm to 808.5nm, gray level of the central point is 136, 137, 134, 136, 138, 134, 138, 137, and average of edge points are 78, 81, 80, 91, 110, 122, 131, 128. There is an increasing from 57.4%, 59.1%, 59.7%, 66.9%, 79.7%, 91.0%, 94.9%, 93.4%. Experimental results indicate that deviation of central pumping wavelength affects pumping energy distribution on cross-section of the rod obviously. When environment temperature rise or drop, pumping power increase or decrease, central wavelength will fluctuate, flattop distribution on cross section of the rod would be changed in agreement of experimental results.

5 STABLE UNIFORM PUMPING DEIGN

To diminish effect of central wavelength drift, a special coating on flow tube can be used. If a 5nm, 10nm, 15nm, 20nm flattop region is expect to be realized in effective absorption coefficient, coating curve can be calculated from the data in Fig.5. If minimum point of the effective absorption spectrum is $\min(\alpha_{eff})$ in the designed region, a coefficient

$$\beta = \frac{\min(\alpha_{eff})}{\alpha_{eff}} \tag{6}$$

should be overlapped on the effective absorption coefficient to realized a region of flattop distribution. By overlapping β on pumping spectrum, a special designed pumping spectrum can be gotten. If this kind of pumping spectrum is realized by laser diode control or coating, a flattop effective absorption coefficient can be gotten. Fig.7 is the optimized pumping laser diode spectrum, which performed on the pumping spectrum in Fig.4.

In Fig.7, d is the flattop region to be designed in effective absorption coefficient spectrum.

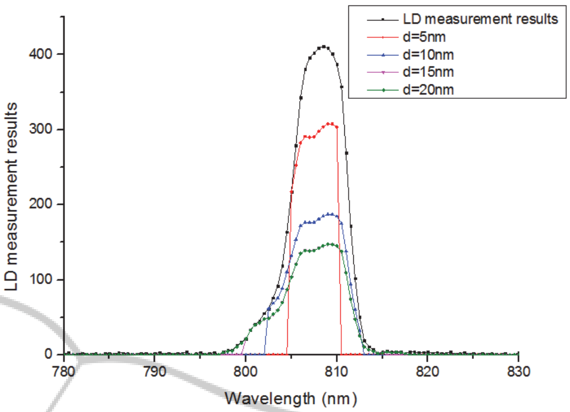

Figure 7: Optimized pumping spectrum with different flatten region.

In conclusion, we present a pumping spectrum shaping idea about side-pumped Nd:YAG amplifier that can realized temperature-stable uniform amplification. By optimizing pumping laser diode spectrum shape, effective absorption coefficient can be controlled to flattop shape, and temperature-stable can be realized. However, the most important fact is how to loading such kind of spectrum on working materials.

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