Phase locking of two beams emitting from a side pumped Nd:YAG slab with self-imaging resonator

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Intracavity phase locking of two beams emitting from a block of Nd:YAG medium side-pumped by laser diode array (LDA) was investigated experimentally. The interference fringes of the two beams occured at the output mirror. The coherent output power of 1.13 W was obtained with combination efficiency of 64.9% and coherence degree of about 60%. Only a metallic wire as a filter located at a suitable position close to the output mirror can efficiently lock the entire structure with less than 8% power loss.

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Many fields such as advanced laser machining and nonlinear effect research require laser sources not only with high output power but also near diffraction-limited beam quality[1], achievement of which is a difficult task at power in the multiple kilowatt range[2]. The beam quality, stability, and heat dissipation of high power lasers are typically inferior to those of low power lasers[3,4], so it is suggested that a combination of several low-power lasers may be advantageous over a single high power one. As usual, there are two ways to combine beams, i.e., coherent and incoherent[5], which are applied in different fields. Compared with the incoherent combination, the coherent combination of laser array can get higher power density on the axis in the far filed. Unfortunately, coherently combining two or more laser output fields encounters a major difficulty to accurately control the relative phase between the output beams so as to ensure constructive interference. In recent years, much attention has been paid to the coherent combination by different approaches, including Talbot effect[6], phase conjugation[7], self-imaging confocal resonator with intracavity spatial filter[8], active phase correction[9], fiber coupler[10], and self-organizing[11], etc.. One of them called self-imaging resonator with a spatial filter has attracted many researchers due to its simplicity for both solid state and fiber lasers[8,12]. Up to now, all the reported phase locking setup by self-imaging resonator was pumped by diode lasers longitudinally, which limits the power increase of a single laser, an alternate way is to pump the medium from sides or edges. Though there is not essential difference for coherent combination between the side and the end pumping lasers, the side pumping approach may be more practicable since side pumping is often used in high power laser system.

In this letter, we demonstrate experimentally phase locking of two beams generating from a block of side pumped Nd:YAG slab by self-imaging resonator with intracavity spatial filter. It is helpful to overcome the limitation of combination of beam from the end pumping laser. 1.13-W output power is obtained when the side pump power is 5.73 W and the combination efficiency is about 65%. The experimental result also shows that only a single wire is located in the interference filed, the laser can operate stably in the in-phase mode.

The experimental setup is illustrated in Fig. 1. Two 55-mm-long laser diode arrays (LDAs) (5.7 W @ 14 Hz) sidely and symmetrically pumped a 55 × 6 × 4 (mm) Nd:YAG slab with absorption coefficient of 0.74 mm^{-1}. The pump beams were along y-direction as depicted in Fig. 2. One side of the crystal and LDA were cooled by thermal conduction on the same copper block cooled by water. The resonant cavity terminated on one side in a flat output mirror (OM) with 10% transmission at 1064 nm and on the other one in a high reflectivity dielectric mirror (HM). The two mirrors OM and HM were set on the focal planes on each side of the converging lens L with the focal length f of 500 mm. The three elements form a confocal Fabry-Perot resonator which can lock the phases of the two beams due to the intrinsic feature of self-imaging resonator[13]. The beam profiles at the HM and OM are related to each other through a Fourier transform, which means that an arbitrary beam profile $E(x, y)$ at the gain elements turns to $E(-x, -y)$ after a round trip, so any symmetric beam ray returns to its initial value after each round trip, and thus a symmetric beam profile about the axis of the resonator reproduces itself after every round trip[14].

The both sides of the converging lens should have antireflection film at 1064 nm in order to improve system efficiency, in our laboratory only one side, however, does. The unperfect coating film leads to more loss, though it does not affect the principle test. Two apertures (each 4 × 2 (mm)), positioned 4 mm apart (between centers), were located closely to one end of the crystal to avoid the evanescent coupling between the two beams as shown in

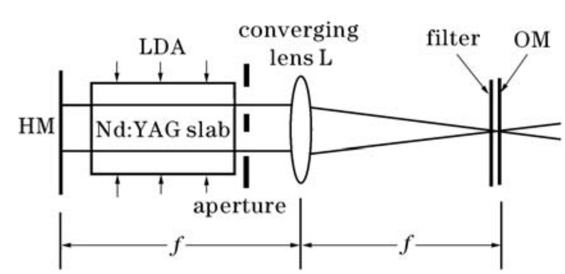

Fig. 1. Schematic diagram of the confocal self-imaging resonator.

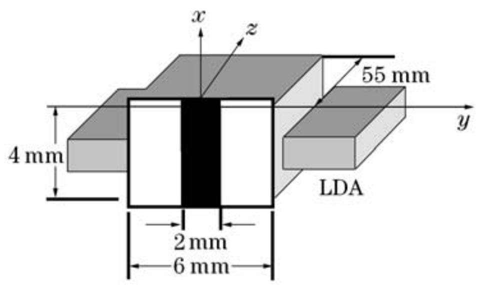

Fig. 2. Dimensions of the crystal and the coordinate system.

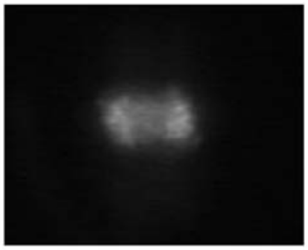

Fig. 3. Near field profile of the output beam without apertures.

Fig. 2. We inserted the apertures and converging lens in the resonator and exchanged the positions of the OM and HM, two spots with about 2-mm dark space occurred at the output beams. When the converging lens and apertures were removed, two spots with weak distinction occurred in the near filed profile of output beam as shown in Fig. 3. So we can conclude that when the apertures are inserted into the resonator the two beams have very weak evanescent coupling, that is to say, the two beams are equal to emit from two independent lasers.

To investigate the influence of element loss, we added the elements step by step. Firstly, the resonator was composed by two flat mirrors with apertures, 1.74-W output power was obtained with pump power of 5.73 W and the corresponding optical-to-optical efficiency was about 30%. Next, the converging lens was inserted in middle of the two mirrors, when the slab was pumped with the same pump power the output power reduced to 1.22 W. A small part of the power decreasing results from the insert loss of lens, while most of it should attribute to only one coating film of the lens. At this time, the beam profile on the mirror OM had no interference fringes apparently for the beams instability. In order to stabilize and prevent the laser from erratic modal jumps by strongly locking the two beams, a metallic wire with diameter of 30 μm was inserted in the resonator closely to the output mirror as a filter. Move the filter vertically to the beam propagation direction to a suitable position, the stable interference fringes occur stably as illustrated in Fig. 4. The relativite intensity distributions are shown in Fig. 5. From it, we can see that three chief peaks occur with the strongest power in the center, so the two beams are in-phase, which is similar to that of phase locking of two beams from fiber lasers[8]. And we can obtain the coherent degree of the composite beam by the definition $\frac{I_{\max}-I_{\min}}{I_{\max}+I_{\min}}$, where $I_{\max}$ is the max intensity at a maximum of the inteference pattern and $I_{\min}$ is the intensity at a minimum. The interference degree in the experiment is about 60%, which is less than that of longitudinally pump beam[12] because the coexistence of basic mode

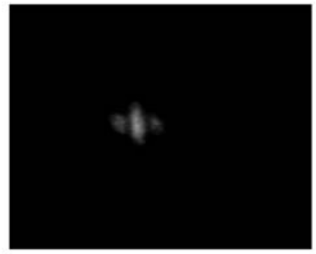

Fig. 4. Interference fringes on the output mirror.

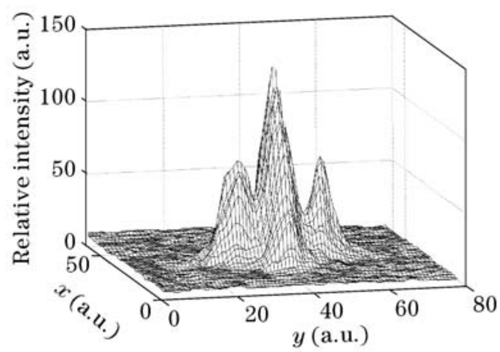

Fig. 5. Relative field profile of the phase locking beams on OM.

Fig. 6. Near field profile of the output beam with apertures.

and high order mode ordinarily occurs at the output beam of side pumped laser. Put a scattered refection plate along the optical axis with 200-mm distance from the output mirror, the beam profile was obtained by charge coupled device (CCD) camera (see Fig. 6). Two separate spots of the beams occurred on the propagation path. The patterns difference on the output mirror and in near field proves that three peaks on output mirror are interference fringes instead of the pattern of high order mode. When the filter was inserted in the resonator, the output power reduced further to 1.13 W with about 8% insert loss and the corresponding optical-to-optical efficiency was 19.7%. Figure 7 shows the relation of the output power and pump power under different conditions. From it, it is clear that the output power increases with the increase of input power and the threshold currents of the LDA are almost equal.

In summary, the coherent combination of two beams emitting from a side pumped Nd:YAG crystal was realized successfully by self-imaging confocal resonator. 1.13-W composite power was obtained with 64.9% combination efficiency and 19.7% optical-to-optical conversion efficiency. The stable interference fringes occurred only with a metallic wire as a filter, and the coherence degree

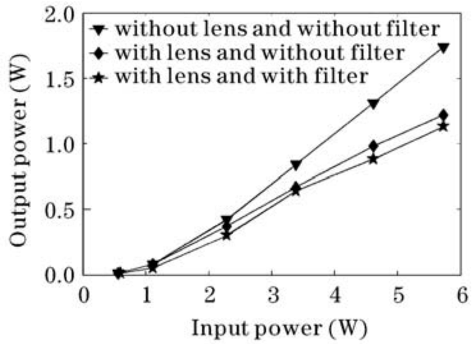

Fig. 7. Output power versus pumping power under the different operating conditions.

is about 60%. It is noted that the spark on the output mirror was found and the coating film was destroyed when the output was more than 1 W. This phenomenon means that the power density is very high on the output mirror and also indicates that the configuration should be improved. In the future, we exchange the position of OM and HM. The HM can use metallic plate with high reflectivity. Two advantages of the improvement are obvious, one is to output the two beams parallelly, which can be reshaped easily; the other is to increase the damage threshold of the mirror at the focus.

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