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Laser diode pumping of an upconversion laser

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Laser diode pumping in commonly applied in all solid state laser devices. In the case of an upconversion laser, *i.e.*, when infrared-to-visible upconversion takes place in a rare-earth doped optical fiber, laser diode pumping is of special interest. Excitation of a single mode optical fiber, typically of core diameter of about 2 μm, requires that the emitting area of the diode must be limited to 1 μm × 3 μm, otherwise its emission cannot be focused to a spot of a few micrometers in size. As we have shown, short focal length lenses of high (NA ≈ 0.4) ensure the best results. Numerical aperture (NA) matching is of less importance.

The upconversion laser built in our laboratory consits of the following components [1]:

1. Excitation – SDL 5420 laser diode. Emitting area 1 μm × 3 μm, maximum output power at 803.5 nm (see Fig. 1) – 150 mW in a single transverse mode, beam divergence, $\theta_{\perp} = 30°$, $\theta_{\parallel} = 9°$.

2. Erbium doped fluoride zirconate (ZBLAN) optical fiber of core diameter around 2 μm.

3. The optical resonator is formed by an input dichroic mirror, transmitting almost totally the pumping beam, and an output mirror, reflecting this beam and transmitting the generated green upconverted fluorescence.

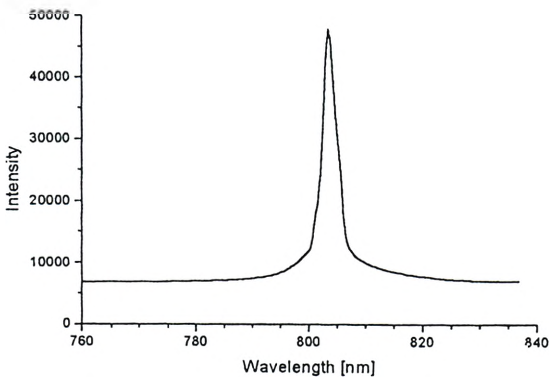


Fig. 1. Laser diode emission at 803.5 nm (in arb. units) taken with an optical multichannel analyzer.

Focusing of the excitation beam onto the entrance face of the fiber, or, more precisely, onto the core diameter is not an easy task. In our case we have used aspheric double-lens systems, AR coated distributed by Thorlabs (Fig. 2).

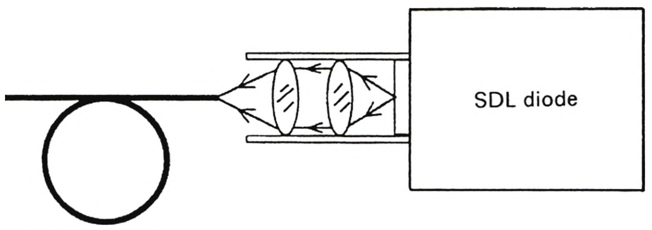


Fig. 2. Aspheric double-lens focusing system used to pump the ZBLAN erbium doped optical fiber of a core diameter of about 2 μm.

The first lens has to be matched to the output beam divergence of the diode, *i.e.*, to an angle of 30°, equivalent to NA = 0.5. This beam does not form a cone, being rather rectangular in shape. The best results can be obtained for an optical fiber of the maximum numerical aperture. The point is that such erbium doped ZBLAN fibers are not commercially available. Usually one can buy fibers varying in NA from 0.15 to 0.35. To obtain laser operation, the excitation power density must be in the range of about 1 MW/cm^2. Thus, optical fibers of larger core diameter require very high excitation power, not available from a single transvere mode diode laser.

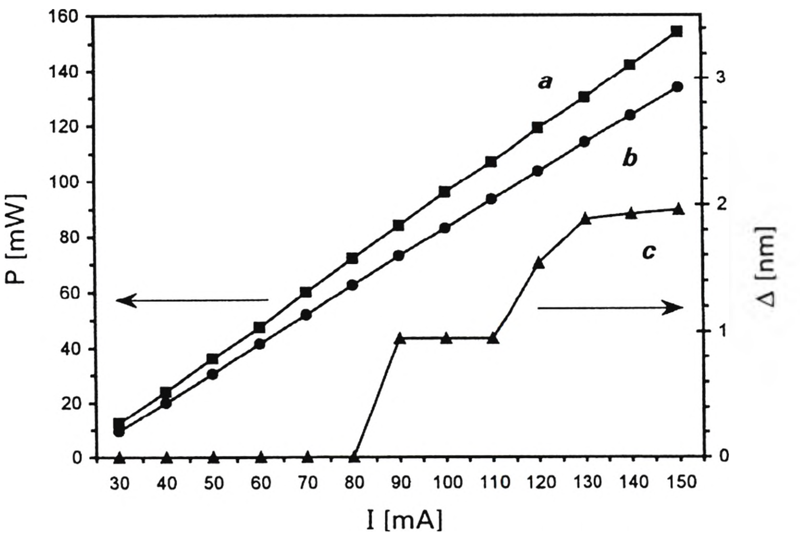
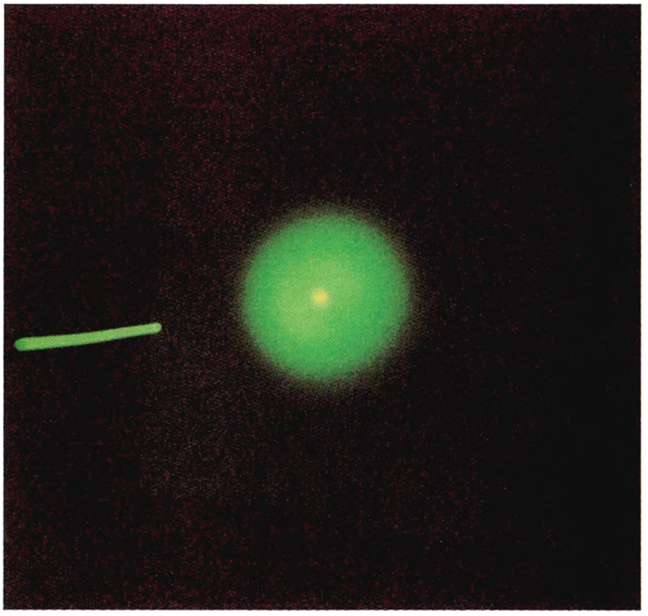
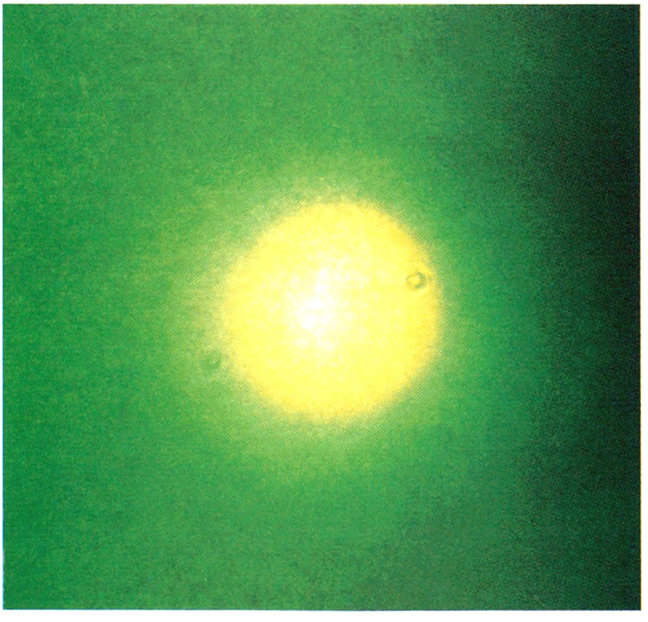


Fig. 3. Output power of the diode (*a*), effective pumping power focused by the double-lens system (*b*) and center wavelength shift (*c*) as function of the driving current.



a



b

Fig. 4. Upconverted fluorescence in the green below threshold (**a**), and above the threshold for laser operation (**b**).

It is very interesting to note that a match of the NA of the focusing system to the NA of the fiber core does not yield the best performance. As a result of our measurements, the most important factor is the "spot diameter" at the focal point of the focusing system. For comparison, let us calculate the spot diameter (at the focus) of two focusing systems with different NA and, of course, with different focal length.

The first one has the following parameters: $f = 6.24$ mm, NA $= 0.4$, lens diameter $D = 5$ mm. Taking into account only the diffraction effect, the "spot diameter" at the focus amounts to

$$d \simeq \frac{2.44 f\lambda}{D} = 2.43 \ \mu\text{m}. \tag{1}$$

This diameter almost perfectly matches the core diameter of our fiber (2.3 μm). However, the NA of this fiber is 0.28. The "length" of the focus area (focus tolerance, according to BORN and WOLF [2]) is

$$l = \frac{4 f^2 \lambda}{D^2} = 5 \ \mu\text{m}. \tag{2}$$

The second focusing system is: $f = 11$ mm, NA $= 0.25$, $D = 5.5$ mm. In this case, $d = 3.9$ μm, $l = 12.8$ μm. The spot diameter is larger than the core diameter (2.3 μm) and, as a consequence, much less excitation power can be introduced to the fiber. The NA matching is much better (0.25 compared to 0.28 of the fiber), but this does not ensure a better coupling of the diode with the fiber. As seen, the diode excitation beam must be focused onto the core with micrometer accuracy in all x-, y- and z-directions.

Using the first focusing system of NA $= 0.4$ and very short focal length, the efficiency of optical coupling (fiber core diameter 2.3 μm) reaches 50%. The second system, with NA almost matched, but with larger focal length, reduced the optical coupling efficiency to 10%, and no laser operation with this system could be obtained.

As seen from Eq. (1), lenses with large focal length cannot be used to concentrate the excitation power onto the small core diameter. The NA matching is of less importance. We did not take into account a few other phenomena (*e.g.*, astigmatism, aberration, asymmetry of the output emission of the diode). It is thus obvious that the efficiency of the optical coupling amounts to only 50%.

The double-lens focusing system used concentrates the output power of the diode into a spot (at the focus) of a few micrometer in diameter. The output power of the diode as well as the effective power focused by this system is shown in Fig. 3. However, one has to be aware of the shift in the center wavelength emitted by the diode with the increase of the driving current. The shift toward longer wavelengths is shown in the same figure (right-hand scale). This shift is a serious problem because it changes the absorbed power in the fiber and, as a consequence, the upconverted fluorescence intensity. Changes of the upconverted fluorescence in a step-wise manner with the increase of the pumping power can be thus fully explained.

In the case of an erbium doped (1000 ppm) ZBLAN optical fiber of a core diameter 2.3 μm, pumped at 803.5 nm, the output upconverted fluorescence at 540 nm emerges in a LP_{02} mode (Fig. 4**a**). However, above the threshold for laser operation the green output beam propagates in a single LP_{01} mode (Fig. 4**b**).

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References

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