Efficient pumping of Rb vapor by high-power volume Bragg diode laser

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A 2 W cw laser diode (LD) with an external cavity produced by a reflecting volume Bragg grating (VBG) demonstrated a spectral width of 7 GHz (full width at half-maximum) at 780 nm. The device output power exceeded 90% of the output power of the free-running LD. The emission wavelength was tuned over a 300 pm range by thermal control of the VBG. Rb vapor was shown to absorb more than 95% of the laser radiation. © 2007 Optical Society of America

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Optically pumped alkali-vapor (Cs, Rb, and K) lasers are attractive sources for high-power applications due to their high quantum efficiency, excellent optical beam quality, and reduced thermal load [1]. These alkali-vapor lasers require optical pump sources that can reliably emit energy within the narrow (~10 GHz) absorption bands of the alkali vapor. There are several approaches for optical pumping of such narrow absorption band media. Rb and Cs vapor lasers optically pumped by Ti:sapphire [1,2] and dye [3] lasers have been reported. It has been demonstrated that the alkali-vapor lasers can be optically pumped by laser diode (LD) arrays with linewidth exceeding several nanometers (a few terahertz); however, the optical-to-optical efficiency of such pumping did not exceed 10% and required high-pressure buffer gasses [4–6]. It was shown that a distributed-feedback LD produced 1 W of output power within 0.1 nm spectral linewidth [7]. Single LDs and laser bars integrated into wavelength selective external cavities with planar diffraction gratings can simultaneously achieve narrow linewidths (hundreds of gigahertz) and high output powers (tens of watts) [8–11].

Recently, an LD bar with a volume Bragg external cavity has shown an output power of more than 10 W with a 7 GHz FWHM spectral linewidth in cw operation [12]. However, this laser had a narrow-line emission with spectral contrast less than 20 dB and a slope efficiency of less than 0.5 W/A. Photothermorefractive (PTR) volume Bragg gratings (VBGs) with higher spectral resolution power in comparison with conventional diffractive gratings have been recently developed [13,14]. This technology has opened new opportunities for the design and fabrication of compact external cavity diode lasers suitable for optical pumping of solid state, fiber, and gas lasers [15]. Spectral narrowing down to the subnanometer range for LDs, bars, and stacks integrated in VBG external cavities has been demonstrated recently [15–17].

In this Letter, we report on the development of a volume Bragg diode laser operating at 780 nm suitable for highly efficient optical pumping of Rb lasers. Cw power up to 2 W within a linewidth of 14 pm (7 GHz) (FWHM) and spectral contrast better than 45 dB are demonstrated.

The volume Bragg laser (VOBLA) consisted of a 150 μm wide and 2 mm long off-the-shelf LD, a fast-axis collimator, and a reflective VBG as a wavelength-selective output coupler. The 17 mm thick reflecting Bragg grating (RBG) in a PTR glass was specially designed and fabricated at OptiGrate. This 5 mm × 6 mm aperture mirror exhibited a 70% diffraction efficiency for plane waves at resonant wavelength, a 30 pm (15 GHz) spectral selectivity (FWHM), and 1° angular selectivity (FWHM). The resonant Bragg wavelength of the RBG at normal incidence (retroreflection) was 779.92 nm corresponding to a refractive index modulation period of 0.26 μm. The RBG and a fast-axis collimator had antireflection coatings to prevent the parasitic reflections. The LD and RBG were mounted on thermoelectrically cooled copper heatsinks with temperature stability of ±0.01 K.

The laser spectral characteristics were studied in cw operation. To evaluate the overall emission spectra of the free-running LD and VOBLA, the laser output radiation was collected into an integrating sphere and was then coupled into an optical spectrum analyzer (OSA) using a single-mode fiber. The spectral resolution of the experimental setup was 15 GHz (30 pm). The laser spectral width and mode structure were initially evaluated using a Fabry–Perot etalon with 15 GHz free spectrum range and 0.8 GHz spectral resolution. Precise measurement of the VOBLA mode structure was performed using a scanning confocal Fabry–Perot interferometer with a 10 GHz free spectrum range and 67 MHz spectral resolution.

Figure 1(a) shows the emission spectra of the free-running (dotted curve) and volume Bragg (solid curve) diode lasers measured at 1 W cw output power. The temperatures of the LD and RBG were 18 °C and 25 °C, respectively. The emission spectrum of the free-running LD had a maximum of ~780 nm and a spectral width of 2 nm (FWHM). The emission

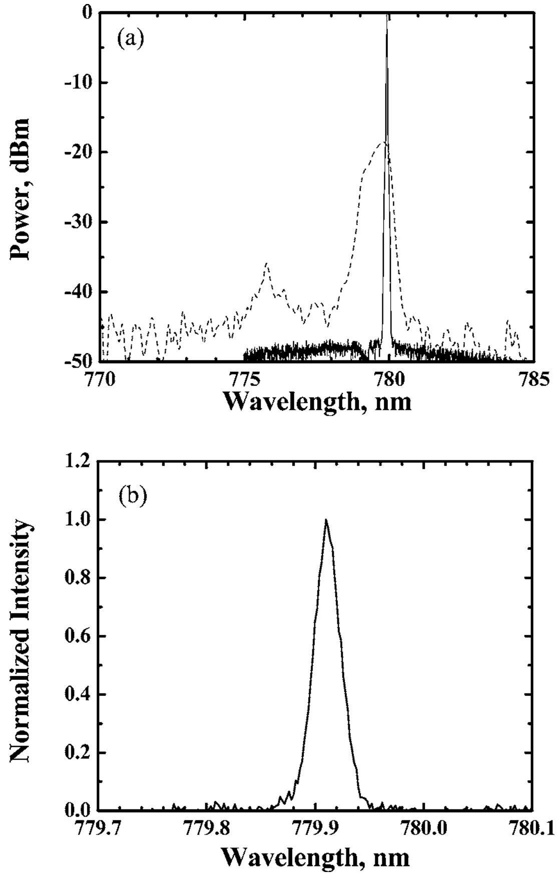

Fig. 1. (a) Emission spectra of free-running (dotted curve) and volume Bragg (solid curve) diode lasers in semilog scale. (b) Emission spectrum of a VOBLA in linear scale.

spectrum of VOBLA was narrowed to 30 pm (15 GHz) FWHM [Fig. 1(b)], which corresponded to the spectral resolution of the OSA. The spectral contrast was better than 45 dB. The VOBLA emission spectrum width insignificantly broadened at higher level of output power.

The VOBLA spectral linewidth was determined by measuring the emission spectrum using a Fabry–Perot etalon with a free spectrum range overlapping the spectral resolution of the optical spectrum analyzer. It was shown that the VOBLA linewidth did not exceed 7 GHz (FWHM). The detailed mode structure of the VOBLA was measured using the scanning confocal Fabry–Perot interferometer. Figure 2 shows the mode structure of the VOBLA producing 1 W cw power. The spectrum repetition spacing equals to the free spectral range (10 GHz) of the scanning confocal interferometer. The external cavity resonator supported up to four modes with ~2 GHz mode spacing and 7 GHz overall spectral bandwidth. This mode spacing is in good agreement with the distance between adjacent longitudinal modes in the given external resonator. Typically, more that 80% of emitted power was concentrated within one or two of those modes. The VOBLA spatial mode distribution measured at 1 W cw output power showed multimode operation with ~6° FWHM of the far-field pattern.

Figure 3 shows that the dramatic spectral narrowing to a 7 GHz linewidth leads to only an approximate 10% decrease of output power. The current threshold decrease and slope efficiency drop resulted from the higher reflection from the external Bragg mirror as compared to the free-running LD. The laser output mirror reflectivity increased from 0.5% to approximately 10% that decreased the device mirror loss in accordance with [18]. To evaluate this result we roughly estimated the VBG reflectivity for the incident divergent beam. The far-field pattern of the free-running LD was measured along the slow axis. The FWHM of the far-field pattern was ~7° compared with the 1° angular selectivity of RBG. So, only one seventh of the LD beam was reflected back by the given VBG, which had 70% reflectivity for the plane wave at resonant wavelength. The VBG reflectivity can be roughly estimated as 10% for the incident LD beam.

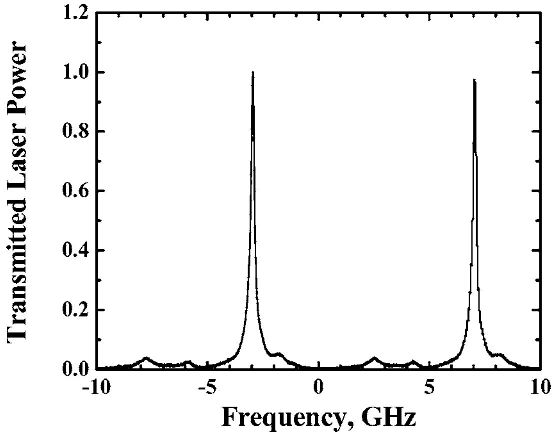

Fig. 2. Emission spectrum of the VOBLA measured by a scanning confocal Fabry–Perot interferometer with 10 GHz free spectral range.

Optical pumping of Rb vapor media requires tuning of pumping laser emission to precisely overlap with the Rb absorption bands. The VOBLA emission spectrum was thermally tuned over a 300 pm spectral range by heating the RBG, which provided a Bragg wavelength thermal shift of 8 pm/K [Fig. 4(a)]. This thermal shift of the wavelength does not deteriorate the width of the laser spectrum.

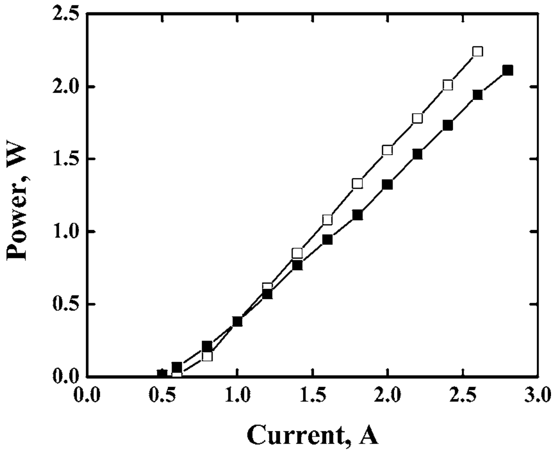

Fig. 3. Cw output power of a free-running (hollow square) and a volume Bragg (solid square) diode laser versus driving current.

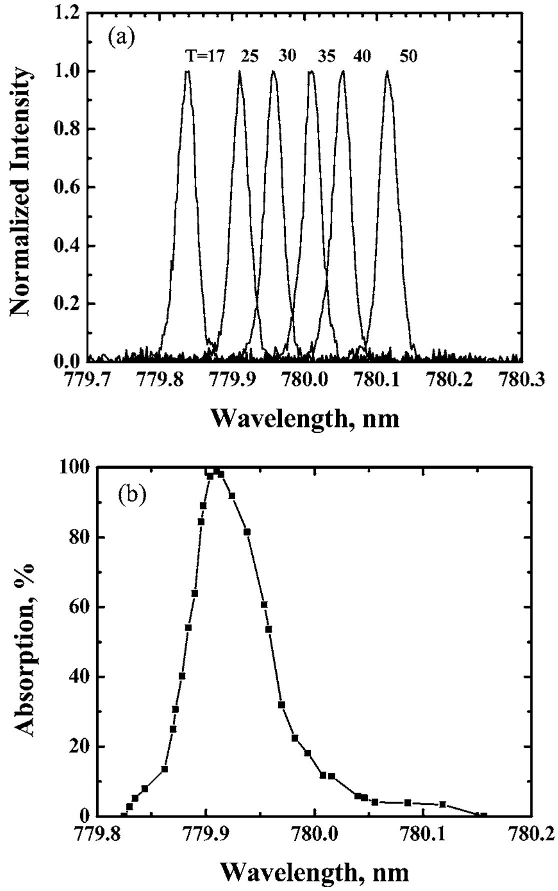

Fig. 4. (a) Emission spectra of a volume Bragg diode laser at different grating temperatures. (b) Absorption of VOBLA radiation by an Rb cell versus central wavelength of emission.

The absorption of the pump light by Rb atoms was measured in a Rb cell at 420 K. The cell contained Rb vapor mixed with C_2H_6 buffer gas. The buffer gas pressure was 300 Torr (0.4 atm). These conditions do not significantly contribute to Doppler and collisional broadening mechanisms of the Rb absorption spectrum. Figure 4(b) shows the absorption of laser radiation by the Rb cell versus central wavelength of VOBLA. The central wavelength was determined as the average weighted wavelength of the emission spectrum recorded by the optical spectrum analyzer. The low-pressure Rb cell absorbed more than 95% of VOBLA radiation at a wavelength of 779.92 nm.

In summary, a diode laser with a VBG output coupler emitting at 780 nm has demonstrated a cw output power up to 2 W with a slope efficiency of 1 W/A, a spectral width (FWHM) of 7 GHz (14 pm), and a tunability of over 300 pm. More than 95% of the laser emission was absorbed by a Rb cell.

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