532nm laser sources based on intracavity frequency doubling of extended cavity surface-emitting diode lasers

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ABSTRACT

We introduce a novel type of cw green laser source, the Protera 532, based on the intracavity frequency doubling of an extended-cavity, surface-emitting diode laser. The distinguishing characteristics of this platform are high compactness and efficiency in a stable, single-longitudinal mode with beam quality $M^2 < 1.2$. The laser design is based on the previously reported NECSEL architecture used for 488nm lasers, and includes several novel features to accommodate different types of nonlinear optical materials. The infrared laser die wavelength is increased from 976nm to 1064nm without compromising performance or reliability. The intracavity frequency doubling to 532nm has been demonstrated with both bulk and periodically poled nonlinear materials, with single-ended cw power outputs of greater than 30 mW.

Keywords: green lasers, visible lasers, diode lasers, frequency doubling, surface-emitting lasers, single mode

1. INTRODUCTION

Continuous-wave green lasers are desirable in many fields such as bio-analytical instrumentation, display technology, optical microscopy, reprographics, entertainment, etc [1]. The wavelength of 532nm is perhaps the most notable in the green spectrum, and it is considered an industry standard in many applications. For many years, 532nm lasers based on solid-state laser technology have been continuously refined and remained unchallenged. Intracavity frequency doubling of 1064nm neodymium lasers has been known since the 1960s. In the 1980s and 1990s, progress in high-power diode lasers capable of pumping solid-state gain medium made it possible to dramatically improve the efficiency and compactness of frequency-doubled lasers. A simplified illustration of a frequency-doubled diode-pumped solid-state laser (DPSS) is shown in Fig.1. More information about the DPSS laser platform including more detailed cavity configurations can be found in the recent book by Risk et al. [2].

![Diagram of DPSS laser cavity](image)

Fig.1. Illustration of main components in a frequency-doubled DPSS laser. The abbreviations HR, HT, and NLO stand for high-reflectivity, high-transmission, and nonlinear optics, respectively.

The 532nm, frequency-doubled DPSS lasers can be designed in a compact package and are able to deliver high-quality TEM$_{00}$ beam with good power stability, pointing stability, and low noise. However, the overall wall-plug efficiency of these lasers remains limited, primarily because of the cooling requirements for the high-power 808nm pump diode laser. It is common to use tens of Watts of electrical power to obtain 5-10mW of 532nm light.
Given the modern trend of improving efficiency and compactness, it would be highly desirable to have a direct diode laser capable of generating 532nm wavelength. However, reliable semiconductor materials having a transition in the wavelength region around 532nm remain elusive. It is possible to improve the efficiency by eliminating the step of pumping the solid-state gain medium (such as Nd:YAG or Nd:YVO₄) by using a diode laser generating 1064nm and doubling it to 532nm without other intermediate steps as illustrated in Fig.2.

We recently introduced a laser platform suitable for doubling 976nm to 488nm [2]. Use of a large-gain-aperture surface-emitting device with an extended cavity configuration allowed us to meet two critical requirements for efficient frequency doubling: (i) high fundamental power, available inside the extended cavity, and (ii) high beam quality. In this paper, we report on extending this platform to the green region of visible spectrum, and discuss the design and performance characteristics of this novel 532nm laser source.

2. 1064nm, SURFACE-EMITTING LASER DESIGN AND RELIABILITY

The Novalux Extended Cavity Surface-Emitting Laser (NECSEL) platform was discussed in earlier publications [2]. Therefore, we will only summarize the main features of this laser platform and describe the characteristics of 1064nm NECSEL chips. The NECSEL structure is illustrated in Fig.3. The NECSEL is an electrically pumped semiconductor laser that has a three-mirror, coupled cavity design. The substrate-emitting die includes a top-side GaAs/AlGaAs epitaxial highly reflective mirror that is doped p-type and a partially reflective mirror that is doped n-type. The mirrors and gain layers (multiple quantum wells) are grown on an n-type GaAs substrate. The critical design parameters for the NECSEL cavity are the gain region diameter, the n-DBR and output coupler (OC) reflectivities, the OC radius of curvature, and the external cavity length. In this design, we can scale the power up (down) by increasing (decreasing) the gain aperture diameter. The OC radius of curvature and cavity length are designed to ensure the maximum overlap of the NECSEL eigenmode diameter 2w₁ at the chip with the gain diameter. The reflectivity of OC at 1064nm can be selected to provide the maximum IR output power at 1064nm. However, for the purposes of maximizing the efficiency of 532nm generation, we choose the OC reflectivity to be maximum possible (nearly 100%) at 1064nm and minimum possible at 532nm.
To design an efficient frequency-doubled laser with second-harmonic output from 5mW to several tens of mW, we usually work in the range of gain aperture diameters between 80μm to 150μm. The optimum diameter is selected to meet the power and efficiency requirements for 532nm output in TEM$_{00}$ mode, while allowing for a compact linear cavity design.

The development of 1064nm NECSEL chips was based on our extensive experience in fabricating reliable and efficient 976 nm devices. The NECSEL epitaxial structure was MOCVD-grown on low defect density n-type GaAs substrates ($< 500 \text{ cm}^{-2}$), as measured by etch pit density, on the (100) plane cut $\sim 2^\circ$ toward $<110>$. The doping levels in the n-DBR and p-DBRs were selected to balance the benefit of lower electrical resistance caused by higher doping with the increase in optical loss due to the increase in free carrier absorption. The gain region consisted of clusters of strained InGaAs quantum wells (QWs) and strain-compensating GaAsP barriers set at the optical anti-nodes. Since the In mole fraction in the InGaAs QWs was significantly higher in the 1064 nm laser diodes than in 976 nm laser diodes, the temperature had to be lower than that used for the 976 nm growths during epi-growth of the gain region and subsequent p-DBR to prevent In out-diffusion from the QWs.

The available power and wall-plug efficiency for 1064nm NECSEL chips based on the initial epitaxial layer design were tested under conditions similar to those selected for 976nm chips. Specifically, we tested the maximum achievable 1064nm power in a concentric extended cavity configuration producing highly multi-transverse-mode output, and maximum achievable 1064nm output power in a cavity optimized for TEM$_{00}$ mode output. For devices with 100μm gain diameter, the peak power was in the range of 300-400mW, and 150-200mW, respectively. The measured wall-plug efficiency for a TEM$_{00}$ output in 1064nm was in the range of 15-20%. This performance level is a little lower than that achieved with the optimized 976nm NECSELs, but is nevertheless more than adequate for the green laser product described here. Improvements in the 1064nm NECSEL efficiency are expected with further optimization of the epitaxial design.

The reliability of 1064nm NECSEL die was demonstrated using the same approach adopted for 976nm NECSELs [3]. High levels of temperature and current stress were applied, acceleration factors for the device degradation determined and the lifetime estimated. Based on the results of these measurements, die lifetimes under normal operating conditions are well in excess of 20,000 hours, i.e. more than sufficient to meet lifetime specified for 532nm Protera™ laser.

3. INTRACAVITY FREQUENCY DOUBLING - DESIGN OF 532nm PROTERA LASER

The development of the Protera-532 (a NECSEL emitting coherent 532nm beam obtained by intracavity frequency doubling) has been similar to that of Protera-488 [2]. The initial goal was to design a 532nm laser producing 5mW in a TEM$_{00}$ mode. To assure low-noise operation, we also designed this laser to oscillate in a single longitudinal mode. The stable, single-transverse (TEM$_{00}$) mode operation was achieved primarily by designing the cavity length and the radius of curvature of the output coupler to obtain optimum overlap of the cavity eigenmode with the gain diameter. This overlap has to remain stable with respect to modest changes in diode current, cavity length, and other parameters that can vary within a range of several percent in a normal manufacturing process. The single-longitudinal mode operation was achieved with the aid of an etalon in the external cavity. The finesse of the etalon was selected to provide sufficient discrimination between the highest-gain longitudinal mode and the other, undesirable, longitudinal modes.

Two design issues required special attention for Protera-532: the choice and optimization of nonlinear material, and the design of the polarization control mechanism. Optimization of nonlinear material is important because we opted not to employ additional focusing optics but instead achieve the required power specification by a simultaneous optimization of the die design and the crystal material and length. This allowed us to keep the cavity design simple, and reduce unnecessary intracavity losses and packaging costs. The polarization control was critical for obtaining the linearly polarized 532nm output beam and for supporting the conditions necessary for the SHG process. The 1064nm surface-emitting die we used for this work possesses circular symmetry and lases in a linear but uncontrolled polarization. Therefore, the polarization had to be controlled in the external cavity.

The first nonlinear material we considered was bulk KTP. This crystal is well known and widely used for generating 532nm in DPSS lasers. The optimum phase-matching configuration in KTP is type-II, i.e. the SHG process requires two
participating fundamental beams that have different (orthogonal) polarizations in the crystal. In our theoretical optimization of the beam diameter, the crystal length, and the requirements on the circulating fundamental (1064nm) power, we used the theory developed by Zondy [4] to describe type-II SHG with gaussian beams. It is also safe to assume the absence of depletion in the fundamental beam. A typical value for the intracavity 1064nm power was around 5W, and could be scaled up or down by changing the chip design. The polarization of the fundamental intracavity beam was controlled with a Brewster plate. Under these conditions, we obtained power levels on the order of 5mW in 532nm wavelength using KTP crystals up to 10mm in length. The primary limiting factor for the 532nm power was the value $d_{\text{eff}} \sim 3$ pm/V of effective nonlinearity in KTP for 1064nm to 532nm conversion. Not surprisingly, lasers using KTP material can meet the required product specifications [6]. The 532nm beams we obtained by frequency doubling in KTP had excellent optical quality with $M^2 < 1.1$.

A promising alternative to KTP is found in periodically poled materials such as PPLN, PPKTP, and PPLT. The effective nonlinearities for 1064nm to 532nm doubling in these materials are several times that of the bulk KTP. Therefore, a simple linear NECSEL cavity can generate several tens of milliwatts in 532nm, or more in more complex cavities. To optimize the crystal length and the gain diameter and the power of the die, we used the theory developed by Boyd and Kleinmann [5] to describe SHG with gaussian beams in the case when both participating fundamental beams are co-polarized. We achieved polarization control in the external cavity by using the crystal itself – a small tilt of the crystal can create enough walkoff between two supported polarizations of the 1064nm light to render one polarization out of alignment. This design allowed us to avoid introducing extra elements increasing optical loss and assembly cost. Similarly to the design with the bulk KTP, the vast majority of lasers assembled with periodically poled materials had the beam quality characterized by $M^2 < 1.1$.

4. TECHNICAL CHARACTERISTICS OF 532nm PROTERA LASER

We next discuss the technical characteristics of Protera-532 lasers such as power stability, pointing stability, and noise [6]. The results presented below were obtained with periodically poled crystals. Our data collected with bulk nonlinear materials suggests that these technical characteristics are not strongly affected by the choice of nonlinear material, but rather represent general properties of Protera laser family, regardless of its wavelength.

The power stability we specify is similar to that for single-longitudinal mode DPSS lasers: <2% over 2hrs of operation in the ambient temperature window ±3°C. The stability is achieved by: (i) temperature control of the critical elements of the laser cavity; (ii) stable opto-mechanical design ensuring excellent passive stability, and (iii) compensation for small power variations by adjusting diode current in the NECSEL device. The long-term stability in a 15mW, 532nm Protera laser is illustrated in Fig.4 in the black curve. The ambient (room) temperature data was also collected and is shown in the gray curve. The power stability is better than 0.5% for room temperature variation on the order of 2°C.

![Power stability trace of 532nm Protera laser](image)

Fig.4. Power stability trace of 532nm Protera laser shown with the room temperature data collected over the same time period. The laser was operating in the “constant power” mode with feedback loop.
Figure 5 illustrates the power stability and noise, shown in the top graph, during the temperature cycling of the base to which the laser head is mounted. The base temperature profile was varied from 10°C to 36°C as shown in the bottom graph. Some correlation of the power and noise to the base temperature can be seen and confirms the quality of the data. The magnitude of these variations is comfortably within our specification for the power stability and maximum noise (<0.2% in the band of 20Hz to 2MHz).

![Figure 5: Power and noise of 532nm Protera laser during the base temperature cycling test.](image)

Pointing stability is one of the critical characteristics for lasers that are designed for high-precision instruments. Our design goal is the same as in 488nm Protera laser, namely maximum variation of $\pm 30 \mu$rad for temperature variation $\pm 3^\circ$C over 2hr time period. Since the pointing is primarily controlled by expansion and stability properties of mechanical parts that are mostly shared in our 532nm and 488nm lasers, 532nm lasers meet this specification. We have also performed experiments utilizing mechanical parts made of low-expansion materials such as invar. The pointing stability was improved to about $2.7 \mu$rad/$^\circ$C.

The long-term pointing trace for Protera-532 is illustrated in Fig.6. The stability is excellent. The minor change in pointing is suspected to be due to the drift of the experimental setup, which can easily exceed the drift in the laser head.

![Figure 6: Long-term pointing stability of 532nm Protera laser](image)
The efficiency of the laser is another parameter that is critical for many applications. Our current Protera-532nm-5mW laser heads typically consume 2-2.5 W of electrical power under normal ambient conditions, and consume around 8W at elevated (~40°C) ambient temperatures. These numbers are comparable to the performance of the best compact frequency-doubled DPSS lasers. However, we expect further improvement in efficiency as we continue our development of higher-power 532nm lasers. Currently, our 15mW prototype lasers (like those used for the test in Fig.4) consume the same amount of power as 5mW Protera lasers. The increase in efficiency comes from the optimization of the die performance and the optimization of nonlinear material. The lasers with over 30mW of 532nm power have already been demonstrated.

5. CONCLUSIONS

In conclusion, we have demonstrated a novel 532nm laser, based on the intracavity frequency doubling of a diode surface-emitting laser (NECSEL). The NECSEL design has been demonstrated at 1064nm with reliability matching or exceeding the reliability of our 976nm NECSELs, which comply with Telcordia requirements [3]. Like the 488nm Protera laser based on the same platform, Protera-532 has low noise and excellent power and pointing stability. Good spatial beam quality is inherent to NECSEL platform, which utilizes an extended-cavity configuration to achieve higher power levels without losing beam quality. The direct use of 1064nm diode laser emitting a high-quality TEM$_{00}$ beam allows us to eliminate the additional pump laser and beam conditioning optics required in the DPSS platform, therefore helping improve compactness and efficiency. Higher-power and higher-efficiency designs are currently under investigation.

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REFERENCES