State of the Art of Compact Green Lasers for Mobile Projectors

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Abstract

We report on progress in development of the low-cost, highly efficient miniature diode-pumped solid-state (DPSS) green laser sources for pico-projectors and other consumer electronics applications with wavelength 532 nm. As Spectralus laser has monolithic microchip structure there are other green lasers with various discrete designs. We are reviewing both approaches in this paper.

KEYWORDS: mobile projector, pico projector, green laser, microchip laser, low noise laser, periodically poled lithium niobate, periodically poled magnesium oxide lithium niobate, PPLN, PPMgOLN, second harmonic generation, intracavity second harmonic generation

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1. Introduction

Pico and micro projectors are becoming more and more popular for stand-alone and embedded applications. Numerous marketing research publications predict market reaching hundreds of millions units by 2016-2018. [1-3] Growing market demands RGB light engine based products with higher brightness and longer battery life. There is compelling reason for laser-based pico projectors to become market leaders. [4-6]. Laser-based pico-projectors are inherently more efficient than LED-based models because of much better optical power throughput due to considerable lower etendue. For example, laser-based compact projectors have been shown to achieve 20lm/W brightness, [7] whereas maximum brightness in LED-based models does not exceed 10lm/W. Thus efficient lasers can provide considerably longer battery lifetime than LEDs. There is another considerable advantage for the laser-based pico-projectors. Laser sources produce narrower-linewidth colors close to primaries and enable much wider color gamut thus creating vivid and life-like images. [4-6]

There are two basic designs for laser-based pico projectors – panel-based and scanning (see, for example refs. 7-9). Scanning projectors employ one or more MEMS mirrors scanning red, green, and blue collimated laser beams to create image. By design this projectors produce image at any distance and do not require focus adjustment. Such type of projection requires laser modulation with the frequency of up to 100 MHz to produce high definition image. Direct semiconductor lasers are the best fit for this application. Blue and red efficient semiconductor direct lasers with wavelengths of 445 and 640 nm are available from a number of vendors. Direct green GaN-based semiconductor lasers have made an impressive progress in recent years. [10-12] Engineering samples with output power 50-80 mW and wavelengths in the range of 515-520nm are becoming available. However relatively low electrical to optical efficiency of these samples (4-5% at 50C) limits application of direct green laser diodes in compact battery powered pico projectors.

Projectors with collimated laser beams at the output have inherent limitation of the image brightness due to the eye safety issue. [13] Maximum brightness of the scanning projectors can be about 20 lm to remain Class 2 laser device that is considered to be eye safe. At a higher brightness these projectors cannot be qualified as a consumer product.

Panel-based projectors do not project image using collimated laser beams at the output. The laser light is diffused over the surface of the whole active area of the reflective DLP or LCOS panel and the reflected light is projected on the screen to create image. [4-9] These projectors operate in the field sequential regime when red green and blue lasers illuminate panel turn with frame rate of about 120 Hz (panel itself operates at 360 Hz). Thus high-speed modulation of the laser source is not required and diode pumped synthetic green lasers based on second harmonic generation can be used in this application along with direct red and blue laser diodes. In such configuration eye safety limitation is reached at much higher brightness of about 280lm while remaining Class 2 laser product. [14] The panel based laser projectors are also focus free in a wide range of distances as well as the scanning type. This also makes laser-based pico projectors more favorable in comparison with the LED based projectors that require focus re-adjustment even when the distance between projector and the screen changes ever slightly.

In RGB light source, a green laser is the major lumen provider (Table 1), therefore development and production of compact, highly efficient, low cost and powerful green laser is critical for commercialization of laser pico-projectors. Desired power levels for such lasers range from 60 to 200 mW average power in pulsed regimes with various duty cycles and repetition rates. We discuss progress in development of the low-cost, highly efficient miniature diode-pumped solid-state (DPSS) microchip green laser sources for pico-projectors and other consumer electronics applications with wavelength 532 nm. Other green laser designs with discrete architectures are also being reviewed.

2. Synthetic Green Laser Sources

While the generation of laser green light via second-harmonic process is very well understood, the main challenge is to meet the set of demands for mobile projection display applications: (i) high wall-plug efficiency ~10% or higher required to enable battery operation, (ii) compact volume <1 cm^3 required for handheld devices, and (iii) low-cost architecture required by consumer electronics industry.

In the following chapters we will describe possible configurations for the green laser source based on the second harmonic generation (SHG). These sources can be classified by two main categories: single pass and intracavity (multi pass) SHG.

3. Green Sources Based on Single-Pass SHG

3.1. SHG in bulk crystals

Second harmonic with a focused laser beam in a bulk nonlinear material is the simplest way to generate green light. In this case bulk material requiring minimum processing can be utilized. The input and output faces are usually polished and either covered with anti-reflective coating or are cut at Brewster angle to minimize optical losses. To achieve higher efficiency the infrared laser beam must be of a good quality and properly focused into the crystal (Fig. 1). Lower input power would require very tight focus for the higher efficiency. However, in this method the interaction length is limited by the length of the beam waist and at some point diffraction effects or approaching damage threshold of the material, begin limiting the conversion efficiency. For example, optical to optical efficiency at 100 mW output is about 5% (corresponding to about 2.5% wall-plug efficiency, WPE). [15] At the same time optical-to-optical conversion efficiency at ~1500 mW green output is considerably higher: about 20% (WPE ~10%). Thus this method is efficient for the output green power levels in the Watt range, not in 50-150 mW range required for the pico projectors.

3.2. SHG in waveguides

Frequency conversion in a planar waveguide solves the limited interaction length issue, thus allowing higher conversion efficiency at lower output green power levels. [16,17] Wall-plug conversion efficiencies have been reported up to 15% at a green power level of about 300 mW (~600 mW IR input) in 8 mm waveguide, [16] and about 5% at about 1000 mW green output (~4W IR input) in a ~20 mm waveguide. [17] Indeed, efficiency is higher in this configuration than in the bulk crystal. However, there is one important issue with this approach. The single-mode waveguide transverse dimensions are on the order of few micrometers. This requires micro-optics to launch diode laser beam into the waveguide and special fixtures to maintain alignment between the IR source and the waveguide with sub-micrometer precision over a wide temperature range. At a device level it is solved by using adaptive mirrors, for example. [16] It is rather ingenious and effective solution, however it adds complexity to the device control electronics and increases device cost. Moreover, waveguide length required for the efficient conversion dictates longer package dimensions thus making the lasers more difficult to fit into the compact pico projector package.

It should be noted that both types of single pass green sources require very good beam profile from the infrared laser diodes for efficient SHG conversion. At the same time linewidth of the laser source must be narrow and stable to remain within the limited spectral bandwidth of the long nonlinear crystal (waveguide). This is achieved by using special semiconductor laser and tapered amplifier structures that increase complexity and therefore cost of the source

4. Green Lasers Based on Intra-Cavity SHG

Intracavity SHG takes advantage of the high optical intensity circulating inside the laser resonator. This intensity is much higher than the pump intensity thus providing high conversion efficiency from infrared oscillating mode (~1064 nm) into second harmonic (~532 nm). It is the most efficient method of generating green output in a wide range of output powers from milliwatts to multiple watts from the single emitter. Intracavity SHG has been utilized in optically [18)] and electrically [19)] pumped semiconductor lasers, and in diode-pumped solid state (DPSS) lasers consisting of discrete component [7,8,20,21)] and in monolithic microchip lasers. [22,23)] We will describe both DPSS approaches here.

4.1. Green laser with intracavity SHG based on discrete components

The laser is based on intra-cavity second harmonic generation of wavelength near 532 nm of DPSS laser. This method has been realized in both single beam in bulk components [7,8)] and single beam and beam array in planar waveguide configurations [20,21)].

In the single beam configuration the laser cavity has discrete structure and consist of $Nd:YVO_4$ gain crystal, highly efficient periodically poled MgO-doped lithium niobate (PPMgOLN) as the frequency doubler and output mirror. Reliable operation with high peak power of 1000 mW with overall efficiency higher than 15% when operating in pulsed regime with duty cycle of 33% required for field sequential LCOS- based projectors has been demonstrated. The laser package volume is about 2.6 cm^3. [7,8)]

A less conventional approach was taken by the authors of refs. 20 and 21. They use separate planar waveguides for both gain ($Nd:YVO_4$) and nonlinear material (PPMgOLN) to form laser resonator. Both waveguides are not connected and proximity coupled without any additional optics. Waveguide structure allows to efficiently remove heat from the gain medium and to create thermal lens confining laser mode in the waveguide plane and decreasing aberrations. In case of waveguide structure with 15 emitters [20] reported in 2008 the output exceeded 11 W with overall efficiency reaching 21%. The single emitter laser reported in 2012 [21] the output of 4 W with optical-to-optical efficiency of up to 40%. The dimensions for the single emitter design quoted by the authors [21] are 0.4 x 7 x 0.5 mm^3. However, these dimensions do not include heat sink and other package components.

Green lasers made with discrete components are very efficient and deliver high power both from the single emitter and from the emitter arrays. They are employed by respective manufacturers in the embedded projectors [8], and in the laser TV sets [20]. It should be mentioned that assembly of these lasers requires active alignment and maintenance of this alignment over a wide temperature range. The discrete nature of these lasers also leads to a relatively large package volume.

4.2. Monolithic green laser with intracavity SHG (microchip)

Spectralus green laser is based on the monolithic microchip based on optically contacted Nd:YVO_4 and periodically 2oled MgO-doped lithium niobate (PPMgOLN). The assembly is alignment-free which makes assembly procedure very simple. Figure 1 illustrates basic design of the microchip laser. Generation of the second harmonic in the intracavity configuration takes advantage of the high optical intensity circulating inside the laser resonator. High nonlinearity of PPMgOLN allows using a very short nonlinear crystal to obtain high conversion efficiency from the pump laser into the green output. The nonlinear crystal length is usually between 0.5 mm and 2 mm and overall microchip length varies from less than 1 to over 3 mm depending on application. This makes Spectralus laser very compact and yet very efficient.

Microchip green laser source is pumped directly (no lenses or other optics between the pump and the microchip) by the off-the-shelf commercially available edge-emitting diode laser with relaxed requirements for output beam properties. Both microchip and laser on a submount are very compact allowing the whole package to be small in size. Microchip components (Nd:YVO_4 and PPMgOLN), as well as the pump lasers, have become commodities over the last few years. Small dimensions of the both gain and nonlinear crystal reduce the cost and size of the microchip. Alignment free assembly is also very cost effective. All together this makes Spectralus' laser source very competitive in cost structure even in comparison with the direct visible laser diodes.

5. Spectralus Atto Lasers: Design and Performance Highlights

5.1. High quality PPMgOLN material

Requirements for the high efficiency of the green laser source demand optimized design and efficient pump source, but most importantly, a very efficient and reasonably priced nonlinear crystal for second harmonic generation. High nonlinearity is very important for compactness of the final design. Our laser utilizes highest quality PPMgOLN manufactured by Spectralus using proprietary technology. Fig. 2 demonstrates typical results of nonlinearity measurements in this material. Nonlinearity d_{eff} typically achieves values of more than 15pm/V (theoretical maximum for this material is about 16 pm/V). Spectralus manufacturing process of periodic structure is very close to semiconductor wafer-level technology and allows mass production with very low cost.

There are several important advantages of the microchip laser based on PPMgOLN in comparison with more conventional microchips based on another popular nonlinear optical crystal KTP ($KTiOPO_4$). First of all nonlinearity of PPMgOLN can be as high as 16pm/V, whereas in KTP its value is about 3.5 pm/V. Thus conversion efficiency of the microchips based on PPMgOLN is considerably higher than that for the KTP-based microchips. KTP microchips cannot operate at high power because of the gray tracking in KTP nonlinear crystal. And last bat not least output polarization of the PPMgOLN based microchips is inherently linear because of the material properties. In KTP microchips polarization state of the output beam changes with temperature. That makes their application in the projection devices, especially based on LCOS panels, more difficult.

5.2. Two miniature packages

Utilizing the very compact configuration of the microchip green laser source we designed two small packages that satisfy dimension requirements for the pico-projector applications. The packages named Atto (12.4 mm L x 6.8 mm W x 3.9 mm H, volume 0.33 cm^3) is shown in Fig. 3 and Atto-K (8.7 mm L x 6.8 mm W x 3.9 mm H, volume 0.23 cm^3) is shown in Fig. 4. Height of both packages is 3.9 mm, meeting requirements for the compact light engines for the embedded pico-projectors and matching the diameter of 3.8 mm laser package used for blue and red laser diodes. Lasers in both packages are based on the same optical design.

The Atto package has a built-in photodiode that can be used for automatic power control. This feature can be useful in designs where each laser has its own photodiode for APC (automatic power control). However, if internal photodiode is not required, a more compact Atto-K package that does not have built-in photodiode can be used. Both packages can support operation of the laser with over 200 mW of average output power with duty cycle 50% (over 400 mW peak power).

5.3. High average power

While our goal of develop miniature and efficient green laser with the average output power of 180 mW has been achieved [22)], our future product development is targeting pico and compact projectors with even higher luminous output. We have previously reported [24)] that both Atto and Atto-K miniature packages can support output power of up to 250 mW and higher.

These results allowed us to introduce new model Atto-180-120-50 designed to operate with average output power of 180 mW at 120 Hz with 50% duty cycle. Both Atto and Atto-K packages support this regime of operation. The laser components and design have been optimized to minimize power consumption of TEC in a wide temperature range. At the same time the package dimensions did not change. Here we report that high power Spectralus Atto lasers maintain high efficiency in the same package yet delivering higher output power.

Temperature range of operation for pico projectors required by consumer electronics applications is about from +10 to +50°C. However, other types of applications require much wider temperature range. As we targeting broader range of applications, we decided to test laser operation from -30 to +60°C. The laser was placed in the environmental chamber and temperature varied across the range of interest. Results are shown in Fig. 5. Output power of 180 mW is stable in the whole temperature range. TEC power consumption is zero in the center of the range and gradually increases and reaches about 1.6W at both range limits (-30°C and +60°C).

5.4. High peak power

As it was described in 5.2 higher power operation can be achieved by increasing duty cycle. However, some projector designs require higher power and still maintain duty cycle of about 30%. To achieve higher power we tested the same microchips with the higher power pump laser diodes on the test bench. Results of this test are shown below in Fig. 6. Pump diode was modulated at 180 Hz with 30% duty cycle. Maximum peak optical power of the pump laser diode was about 2.5 W. At the highest pump power level green output of over 560 mW has been achieved with optical-to-optical efficiency of about 23%. Peak optical-to-optical efficiency of about 30% was achieved at the peak output power of about 450 mW. These results prove that high peak powers are achievable using Spectralus microchip lasers.

6. Summary

Spectralus' green laser platform offers a miniature, highly efficient, and low-cost solution to a broad range of application such as mobile pico and compact projector, instrumentation and others. We have extended range of operation of Spectralus' Atto laser platform in two miniature laser packages. We have demonstrated the following: high peak power (>500 mW), high average power (>200 mW), and broad temperature range of operation (-30 to 60°C).

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Figure Captions

Fig. 1. (Color online) Schematics of the microchip laser optical train.

Fig. 2. (Color online) Typical nonlinearity profile measured in the 1-mm-thick PPMgOLN material produced by Spectralus.

Fig. 3. (Color online) Miniature laser package Atto with photodiode available on board.

Fig. 4. (Color online) Miniature laser package Atto-K with no photodiode.

Fig. 5. (Color online) Test results of Atto-180-120-50 (180 mW-120 Hz-50%) in a wide temperature range from -30°C to +60°C. TEC power consumption does not exceed 1600 mW at low and high temperature limits.

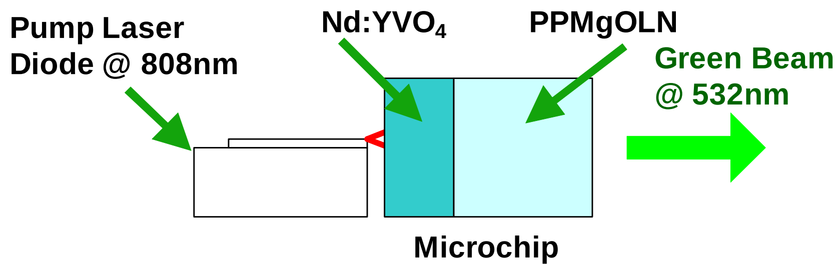
Fig. 6. (Color online) Output of Spectralus microchip laser optimized for high peak power operation. O2O: optical-to-optical efficiency. Repetition rate: 120 Hz, duty cycle: 30%.

Table

Table 1. RGB laser light source efficiency and lumen output referenced to a 200 mW green laser.

	Red 640nm	Green 532nm	Blue 450nm
Photopic response	0.175	0.885	0.038
Lumens per 1 W of laser output	120	604	26
Fractions for D65 white (%/lm)	23.1	74.7	2.3
Fractions for D65 white (%/W)	47.8	30.6	21.7
Average output power (mW)	312.2	200.0	141.6
Average luminous flux (lm)	37.3	120.9	3.7
Wall-plug efficiency (%)	25	14	10
Electrical power consumption (W)	1.25	1.43	1.42
Total RGB output in D65 white (lm)		162	
Total electrical power consumption (W)		4.1	
RGB laser source efficiency (lm/W)		40	

Figures



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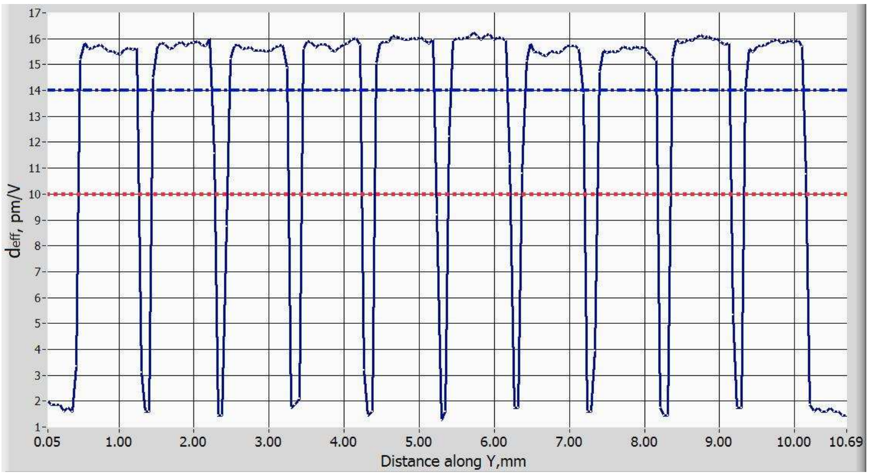


Fig. 2. (Color online) Typical nonlinearity profile measured in the 1-mm-thick PPMgOLN material produced by Spectralus

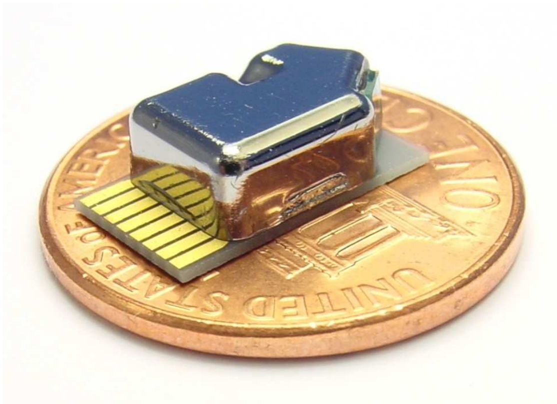


Fig. 3. (Color online) Miniature laser package Atto with photodiode available on board.

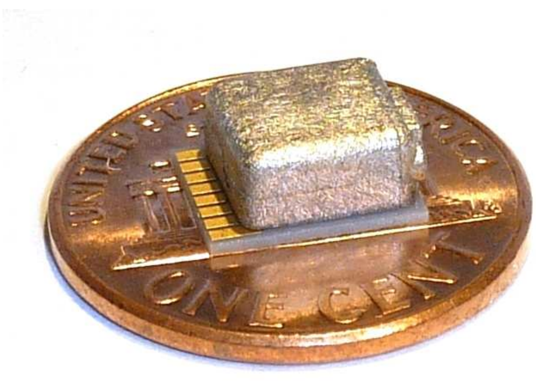
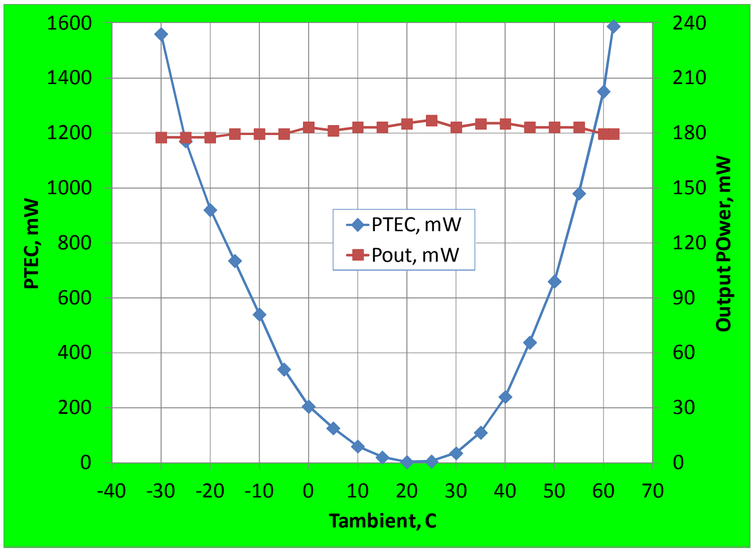


Fig. 4. (Color online) Miniature laser package Atto-K (with no photodiode on board).



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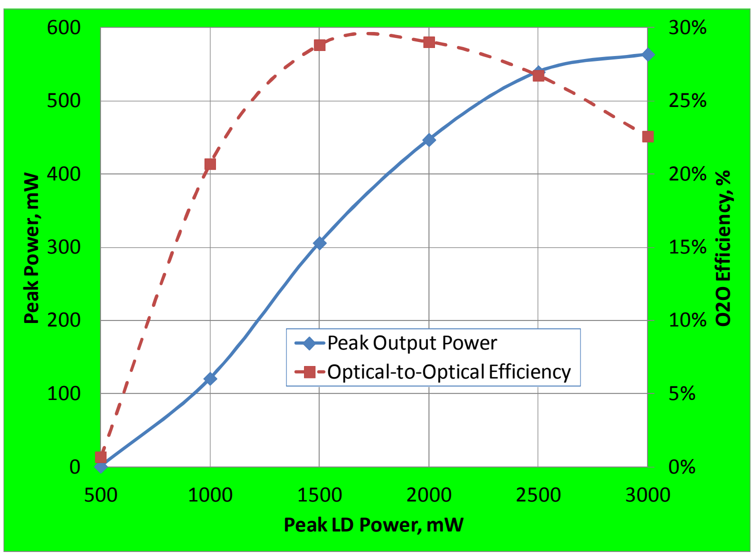

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