Laser Ignition Spin-Off: Giant Pulse UV Microchip Laser

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Giant pulse Nd:YAG/Cr³⁺:YAG passively Q-switched microchip laser, developed for laser ignition, generates several MW peak power sub-nanosecond width pulses. However, this output cannot be used, as it is, for wavelength conversion, since the output polarization is not stable. We redesigned the laser by using [110]-cut Cr³⁺:YAG, instead of the normally used [100]-cut, to obtain stably linearly polarized MW peak power output for efficient wavelength conversion. Using this compact microchip laser, we have achieved efficient second to ninth harmonic generation. In particular, we have designed a palm-top size giant pulse UV laser giving > 4 MW, 150 ps pulse width, 100 Hz output at 266 nm. We have also demonstrated ninth harmonic generation (118 nm) in xenon gas, using the giant pulse microchip laser.

Key Words: UV laser, Nonlinear optics, Wavelength conversion, Harmonic conversion, Microchip laser

1. Introduction

High peak power, pulsed ultraviolet (UV) lasers are useful for many applications, such as materials microprocessing, fast prototyping, laser deposition, photoionization, etc. However, the large size and high cost of pulsed UV lasers has drastically limited their use.

Microchip lasers provide high peak power in a compact, low-cost configuration. This can be effectively used for wavelength conversion, as reported earlier. However, the peak power of the microchip lasers used was in the kilowatt range and so the wavelength conversion efficiency achieved was modest. We have been working on the development of very compact, giant-pulse (> 1 MW peak power) Nd:YAG/Cr³⁺:YAG microchip lasers using quasi-continuous-wave (QCW) pumping for several applications. We have used these lasers to develop a laser ignition module that can be used in automobiles to replace spark-plugs. These lasers have a high peak power (> 6 MW). However, the output of these lasers is not stably linearly polarized. Hence, they cannot be used, as it is, for efficient wavelength conversion. Earlier, we proposed the use of [110]-cut Cr³⁺:YAG, instead of the normally used [100]-cut Cr³⁺:YAG, to achieve a stably linearly polarized output. With this approach, we have now obtained several megawatt peak power, with the desired polarization state.

In this paper, we review the results of wavelength conversion using our microchip laser. As we shall explain, high efficiency wavelength conversion was possible due to the use of the sub-nanosecond pulse width region between 100 ps to 1 ns.

We have achieved 85% second harmonic generation (SHG) efficiency using Type I LiB₃O₃ (Lithium Triborate, LBO) crystal and 60% fourth harmonic generation (FHG) efficiency using fluxless-grown β-BaB₂O₄ (β-barium borate, BBO) crystal. These results were obtained under optimum conditions using focusing optics to input the optical beam into the nonlinear crystals.

The use of focusing optics increases the size of the UV laser. Taking advantage of the high peak power of the microchip laser to design a compact UV laser, we eliminated the focusing optics. Although this reduces the wavelength conversion efficiency to some extent, we could achieve a palm-top size, giant pulse UV laser giving > 4 MW, 150 ps, 100 Hz output at 266 nm.

To demonstrate the potential of the sub-nanosecond pulse output from the microchip laser, we have also performed ninth harmonic generation (118 nm) in xenon gas. This was successfully used for single photon ionization of benzene in a mass-spectroscope.

2. ‘Pulse Gap’ region for wavelength conversion

We call the pulse width region from 100 ps to 1 ns as the ‘pulse gap’ region because it is not easily obtainable by either actively Q-switched lasers, or mode-locked lasers. This pulse width region, attainable by passively Q-switched lasers, has a unique advantage for wavelength conversion. Consider the wavelength conversion efficiency given by the following equation

\[ \eta = \tanh^2 \left( \sqrt{\kappa L \left( \frac{P_s}{A} \right)^2} \right) \]

where \( L \) is the length of the nonlinear crystal, \( P_s \) is the input laser power, \( A \) is the effective input beam area and \( \kappa \) is a constant that depends on the nonlinear crystal and the input wavelength. When performing wavelength conversion with nanosecond lasers, since the peak power is not very high, the laser beam is normally focused in the nonlinear crystal to increase the laser intensity \( P_s/A \). However, this effectively limits \( L \) due to the walk-off of the nonlinear crystal, and so the conversion

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efficiency gets limited.

When using femtosecond lasers, the laser beam is not required to be focused, as the peak power is already high. However, femtosecond lasers have a wide spectral width. Consequently, \( L \) is normally limited to a few hundred micrometers to avoid the laser pulse from getting broadened due to group velocity mismatch. Therefore, the small \( L \) again limits the wavelength conversion efficiency.

However, for a laser having a pulse width in the ‘pulse gap’ region (100 ps to 1 ns), the peak power is high and the spectrum width is still small. Hence, it is possible to use a weakly focussed, or a parallel, beam in a long nonlinear crystal, making both \( L \) and \( P/A \) large. This enables high wavelength conversion efficiency in the ‘pulse gap’ region. Hence, microchip lasers, which provide a pulse width of a few hundred picoseconds, are very suitable for wavelength conversion.

3. Laser Structure

A schematic of the laser structure is shown in Fig. 1. A 4 mm-thick 1.1 at. % [111]-cut Nd:YAG crystal was pumped in the QCW regime by a fiber-coupled (600 μm core diameter, 0.22 NA) 100 W, 808 nm laser diode at 100 Hz. An [110]-cut Cr4+:YAG crystal was used for passive Q-switching. Different initial transmission, ranging from 10% to 50%, Cr4+:YAG crystals were used. A flat coupler with a transmission of 50% was used at the output. The total cavity length was 11 mm.

A thermoelectric cooler was used to maintain the Nd:YAG and Cr4+:YAG crystal temperature at 25 °C.

The air-cooled laser had total dimensions of 60 mm × 52 mm × 61 mm.

4. DUV (266 nm) generation

We used the laser structure described in the previous section with a 10% initial transmission Cr4+:YAG crystal. We obtained a stable, linearly polarized output of 3 mJ pulse energy, 230 ps pulse width and 100 Hz repetition rate at 1064 nm for 100 W, 275 μs width 100 Hz QCW pumping. This resulted in a peak power of 13 MW. The polarization of the output beam was stable and the ratio between the normal modes was better than 100:1.

The output beam diameter was 0.8 mm and the \( M^2 \) factor was 3 approx. We aimed for maximum output energy, rather than an ideal Gaussian beam.

Deep ultraviolet (DUV), at 266 nm, was generated by using the set-up shown in Fig. 2.

SHG was obtained by using a 5 mm × 5 mm cross-section, 10 mm-long Type I LBO crystal cut at \( \theta = 90°, \phi = 11.4° \). The crystal was dual-band anti-reflection coated at 532 nm and 1064 nm. We chose LBO for SHG due to its high enough damage threshold and a relatively large angular acceptance bandwidth that permits efficient SHG with multi-mode laser radiation. The spectrum width of the laser is 5 pm approx., which is much smaller than the acceptance bandwidth of Type I LBO (1 nm-cm). We performed SHG in the critical phase matching (CPM) regime, since any crystal temperature control mechanism would increase the size of the UV laser, and so, diminish the size-advantage offered by compact microchip lasers. The LBO crystal was placed in a groove cut in a sphere that could be freely rotated to adjust the 3-axis angular orientation of the crystal. This mechanism reduced the overall size of the laser. There was no intervening optics between the microchip laser and the LBO crystal. By proper angle-tuning, we could obtain 1.7 mJ pulse energy, 177 ps pulse width output at 532 nm. This gave a peak power of 9.5 MW and a conversion efficiency of 73%. Although this conversion efficiency is lower than the maximum conversion efficiency of 85% obtained by us under optimum conditions, when optics is used to launch the laser beam into the LBO crystal,\(^1\) it is still quite high due to the high input peak power.

For FHG, we used a 5 mm × 5 mm cross-section 6 mm-long Type I BBO crystal cut at \( \theta = 47.7°, \phi = 0° \) in the CPM regime. The crystal was dual-band anti-reflection coated at 532 nm and 266 nm. Again, no intervening optics was used between the LBO and BBO crystals. A BBO crystal was used for FHG because of its ease of handling, as it is less hygroscopic compared to CsLiB\(_3\)O\(_6\) (CLBO). The BBO crystal was also placed in a groove cut in a sphere that could be freely rotated to adjust the 3-axis angular orientation of the crystal.

The BBO crystal holder was rotated to maximize the output at 266 nm, which was measured after two dichroic mirrors to separate the fundamental and 532 nm from the 266 nm beam. It was found necessary to finely retune the LBO crystal in order to maximize the 266 nm output. We believe that this is due to the fact that we are not optimizing the conditions at each stage.

We could obtain 650 μJ pulse energy, 150 ps pulse width output at 266 nm. This gives a peak power of 4.3 MW and a conversion efficiency of 45.3%. The FHG conversion efficiency is lower than 60% that was obtained under optimum focusing conditions using a fluxless-grown BBO crystal.\(^2\) However, the UV laser can be made more compact and stable by eliminating the optics between the LBO and BBO crystals.

The overall conversion efficiency, from 1064 nm to 266 nm, is 33% approx. without the use of any intervening optics. In comparison, when the wavelength conversion is done under optimized conditions, using intervening optics, the conversion efficiency from IR to UV is 51%.\(^3\)

The \( M^2 \) of the output 266 nm beam was measured by the knife-edge method and was calculated to be 2.4 and 2.6 in the vertical and horizontal directions, respectively.

A photograph of the DUV laser prototype is shown in Fig. 3. The prototype has dimensions of 150 mm × 35 mm × 45 mm. Along with a thermoelectric cooler and a fan, which allow...
stable operation under ambient temperature fluctuations, the dimensions are 155 mm × 95 mm × 60 mm. Figure 4 shows such a prototype. The dimensions can be further reduced by optimization of component placement and packaging.

5. VUV (118 nm) generation

Vacuum ultraviolet (VUV) at 118 nm was generated by using the third order nonlinearity of xenon (Xe) gas.

At first, the third harmonic of Nd:YAG was generated by using Type I and Type II LBO crystals, as shown in Fig. 5. In this case, the cavity length of the microchip laser was 10 mm and a 30% initial transmission Cr<sup>4+</sup>:YAG was used. The output at the fundamental wavelength was 3 mJ, 345 ps at 100 Hz, giving a peak power of 8.7 MW. The laser beam diameter was 0.8 mm approx.

We used a 10 mm-long Type I LBO crystal in the CPM regime for SHG. No optics was used between the two LBO crystals. It was necessary to slightly retune the first LBO crystal, in order to maximize the THG output. By doing so, we increased the overlap between the residual 1064 nm beam and the 532 nm beam in the second LBO crystal. Consequently, we obtained an output of 0.65 mJ, 170 ps, 100 Hz at 355 nm. This gave a peak power of 3.8 MW and a conversion efficiency of 76% from 532 nm to 355 nm. The conversion efficiency from 1064 nm to 355 nm was 44%.

The 355 nm beam, obtained through THG, was used for ninth harmonic generation in the experimental set-up shown in Fig. 6 (a). Figure 6 (b) shows a photograph of the Xe gas cell with a time-of-flight mass-spectroscope (TOFMS) in the background. The 355 nm beam, was focused into a Xe gas cell using a 200 mm focal length lens. At the input of the Xe gas cell, another lens of focal length 100 mm, whose position could be adjusted, was used to finely adjust the 355 nm spot in the gas cell. The output 118 nm was used to ionize benzene in a TOFMS. The ionized particles were detected by a micro-channel plate (MCP) detector in the TOFMS.

The detected output signal is shown in Fig. 7. The output signal, which is proportional to the 118 nm generation, nearly follows a cube function of the 355 nm pulse energy, as expected, for energies less than 600 μJ. For greater energy, there is an onset of saturation. We believe that the saturation is due to self-phase modulation at high intensity, which deteriorates the phase matching conditions.

Figure 8 shows the mass-spectrum with benzene for different input pulse energies at 355 nm. The mass-spectroscope...
Signal showed no fragmentation, confirming single-photon ionization.

The ability to generate 118 nm VUV using a compact picosecond microchip laser is a significant development for both scientific and industrial fields. For instance, we found that some gases which could not be detected using a flash-lamp pumped 12 mJ, 10 ns, 355 nm Nd:YAG laser as a source for Xe tripling, could be detected by using the 600 μJ, 170 ps, 355 nm output obtained from the microchip laser. The sensitivity of our ps laser is an order of magnitude greater than that of the ns laser. We intend to further study the interaction of picosecond 118 nm radiation with gases, and compare it with that using nanosecond 118 nm radiation.

For industrial use, the biggest advantage of using the microchip laser is its compactness and ruggedness. We can fabricate the microchip laser based 355 nm system in a palm-top size design, as we have done for the 266 nm system discussed in Section 4. Having done so, the 355 nm laser module can be mounted adjacent to the Xe gas cell. This will eliminate time-consuming laser alignment procedures, besides making the complete system very compact and portable.

6. Conclusion

We have demonstrated efficient wavelength conversion, using the ‘pulse gap’ sub-nanosecond pulse width region, which is attainable by a compact passively Q-switched microchip laser. Using this phenomenon, we have designed very compact UV lasers at 266 nm and 355 nm.

At 266 nm, we obtained 650 μJ, 4.3 MW peak power, 150 ps, 100 Hz pulsed output. We have achieved 73% SHG conversion efficiency using a LBO crystal and 45% FHG conversion efficiency using a BBO crystal, without using any optics before the nonlinear crystals. This gives 33% conversion efficiency from IR to VUV in a very compact size laser.

At 355 nm, we obtained 650 μJ, 3.8 MW peak power, 170 ps, 100 Hz pulsed output. The conversion efficiency was 76% from 532 nm to 355 nm and 44% from 1064 nm to 355 nm. Again, no optics was used before the nonlinear crystals.

The 355 nm output was used to generate the ninth harmonic at 118 nm in a Xe gas cell. The generated ninth harmonic was used to demonstrate single photon ionization of benzene in a TOFMS.

The results presented here will be useful for many applications, such as, single photon ionization, UV laser induced breakdown spectroscopy, pulsed laser deposition and materials microprocessing.

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