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Modulation of Frequency Doubled DFB-Tapered Diode Lasers for Medical Treatment

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ABSTRACT

The use of visible lasers for medical treatments is on the rise, and together with this comes higher expectations for the laser systems. For many medical treatments, such as ophthalmology, doctors require pulse on demand operation together with a complete extinction of the light between pulses. We have demonstrated power modulation from 0.1 Hz to 10 kHz at 532 nm with a modulation depth above 97% by wavelength detuning of the laser diode. The laser diode is a 1064 nm monolithic device with a distributed feedback (DFB) laser as the master oscillator (MO), and a tapered power amplifier (PA). The MO and PA have separate electrical contacts and the modulation is achieved with wavelength tuning by adjusting the current through the MO 40 mA.

Keywords: Visible lasers, distributed feedback lasers, frequency doubled lasers, pulsed lasers.

1. INTRODUCTION

Visible lasers, and in particular green lasers, are of great interest for a wide range of applications. Some of these applications, such as laser displays[1] and ophthalmology[2] require pulse on demand operation of the green light. Ophthalmologists use green lasers to create controlled burns on the retina of the eye. This can be used to treat for example retinovascular macular edema or detachment of the retina, both of which can cause blindness if left untreated. To obtain the burns the ophthalmologist typically uses a laser pulse with a duration of at least 50 ms with a power of several hundreds of milliwatt[3]. In recent years, however, it has been shown that it might not be necessary to introduce an actual burn on the retina to obtain a treatment effect. Instead the treatment can be done with a train of µs pulses with a pulse energy below the burn threshold which increases the patients comfort[4].

Currently the most widely used lasers for ophthalmology treatments are frequency doubled diode pumped solid state (DPSS) lasers where a laser crystal, such as neodymium doped yttrium-aluminum-garnet (Nd:YAG), is pumped with a diode array and intra cavity frequency doubled. Such systems can achieve modulation frequencies of a few kHz[5], but few commercial systems are capable of going below 50 ms pulse lengths without an external modulator. In the end the achievable bandwidth of DPSS lasers are limited by the 100 µs to 300 µs upper state lifetime of the laser crystals. A similar technology which can achieve significantly higher modulation speeds is the optically pumped semiconductor laser (OPSL), where the laser crystal is replaced by a semiconductor material. OPSLs can achieve multiple watts of output power and µs pulse durations[6]. Unfortunately, both laser types are expensive and they suffer from a low wall-plug efficiency which often leads to a need for water cooling.

The ideal laser for almost all applications is a laser diode emitting directly at the relevant wavelength. This is especially true for applications where arbitrary modulation is needed, since the bandwidth of the semiconductor material is typically in the GHz range. Unfortunately, there are currently no high power laser diodes emitting in the green or yellow spectral range. By frequency doubling of near infrared (NIR) diode lasers these wavelengths become achievable. NIR laser diodes with tapered amplifiers are now commercially available, and single pass frequency doubling of a 9.5 W distributed Bragg reflector (DBR) tapered laser diode has so far generated 3.7 W of green light[7].

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The laser diode can be gain-switched with a very high bandwidth. The applied current can be as high as 10 A, and gain switching will therefore introduce significant thermal fluctuations of the laser chip, which in turn introduces fluctuations of the wavelength. To achieve efficient single pass frequency doubling periodically poled non-linear crystals with a length of several cm are used. This leads to a wavelength acceptance bandwidth[8] which is significantly smaller than the wavelength fluctuations of the laser diode during gain-switching. Therefore, gain switching is ill-suited for µs pulsing. Alternatively, the limited wavelength acceptance bandwidth of the non-linear crystal can be used to modulate the green output power by wavelength detuning the laser diode. This concept has previously been demonstrated for a blue laser system for optical storage[9] and with a green laser system for laser displays[10]. In both cases, DBR lasers without tapered amplifiers, together with non-linear crystals with ridge waveguide channels were used, however neither the lasers nor the crystals[11] can be scaled to the power levels needed for medical treatment.

Power modulation of the second harmonic (SH) light, using bulk non-linear crystals and DBR-tapered laser diodes, has also previously been demonstrated. The achieved modulation depth was 90%, and was limited by the longitudinal mode structure of the laser diode[12]. A higher modulation depth has been achieved for a similar system, but required heating the diode to 50°C[13].

In this work we present a laser system based on single pass frequency doubling of a distributed feedback (DFB) master oscillator power amplifier (MOPA), and demonstrate modulation of the second harmonic light by wavelength detuning. We show how the longitudinal mode structure of the laser diode is advantageous for the detuning scheme and achieve a modulation depth above 97% up to 10 kHz.

2. SETUP AND RESULTS

Figure 1 shows a sketch of the setup. The laser diode was a DFB MOPA from QPC Lasers and it is mounted p-side up to allow for separate contacts to the DFB master oscillator (MO) and the tapered power amplifier (PA). When the DFB MOPA was stabilized at 20°C and operated at 150 mA over the MO and 4 A over the PA, the output power was 3 W. The output of the DFB MOPA was collimated and passed through an optical isolator. A half-wave plate and polarizing beam splitter was used to pick out a small portion of the beam which was split in two and focused onto a photodiode and into a fiber coupled scanning Fabry-Pérot interferometer (FPI). The photodiode was used to monitor the NIR light during modulation and the scanning FPI was used to monitor the spectral behavior of the laser diode. The light transmitted through the PBS was passed through a second optical isolator and focused into a 50 mm long periodically poled lithium niobate (PPLN) crystal, after which the NIR light was dumped and the green light was split using an uncoated wedge. The transmitted green light was monitored using a thermal power meter and the reflected green light was focused onto a second photodiode.

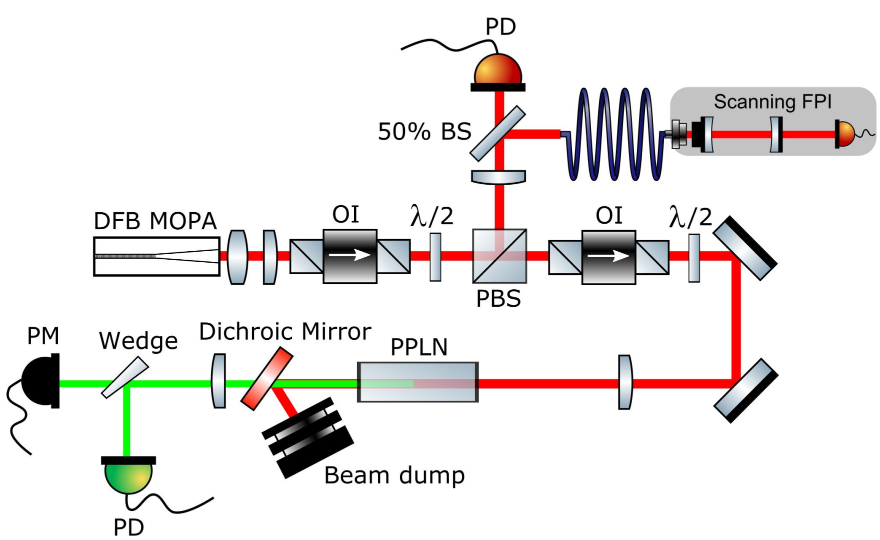

Figure 1. The setup. OI: Optical Isolator, λ/2: Half wave plate, PBS: Polarizing beam splitter, BS: Beam splitter, PD: Photodiode, FPI: Fabry-Pérot interferometer, PM: Thermal power meter, PPLN: 50 mm periodically poled lithium niobate.

The main problem with SH power modulation by wavelength detuning is the longitudinal mode structure of the laser diode. When the current through a laser diode is changed the longitudinal mode will experience discrete hops, resulting in a non-continuous scan of the wavelength. The wavelength change from a mode hop can easily be on the same order of magnitude as the acceptance bandwidth of the non-linear crystal and therefore it is important that the laser always finds the correct mode when a pulse is needed. Figure 2 shows the peak wavelength of the MOPA versus the current through the MO. The current was first scanned up and then back down, without showing mode hysteresis. This means that the laser can be scanned across modes during pulsing without destabilizing the pulse peak power.

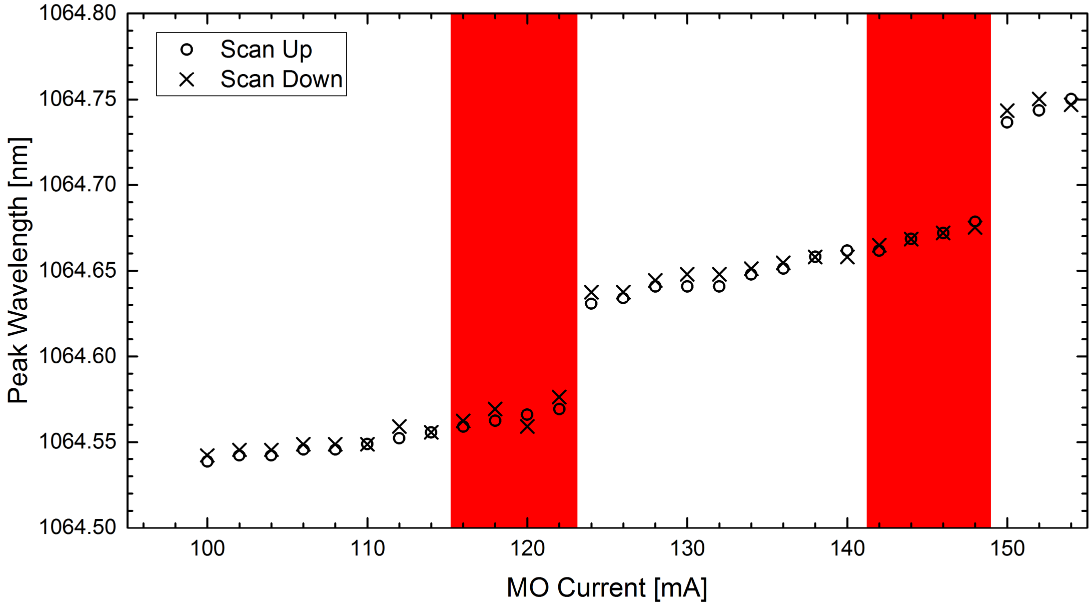

Figure 2. Longitudinal mode structure of the DFB MOPA. The laser exhibited no mode hysteresis and the mode hops resulted in an increased wavelength for increasing currents. The red background indicates regions of multimode behavior.

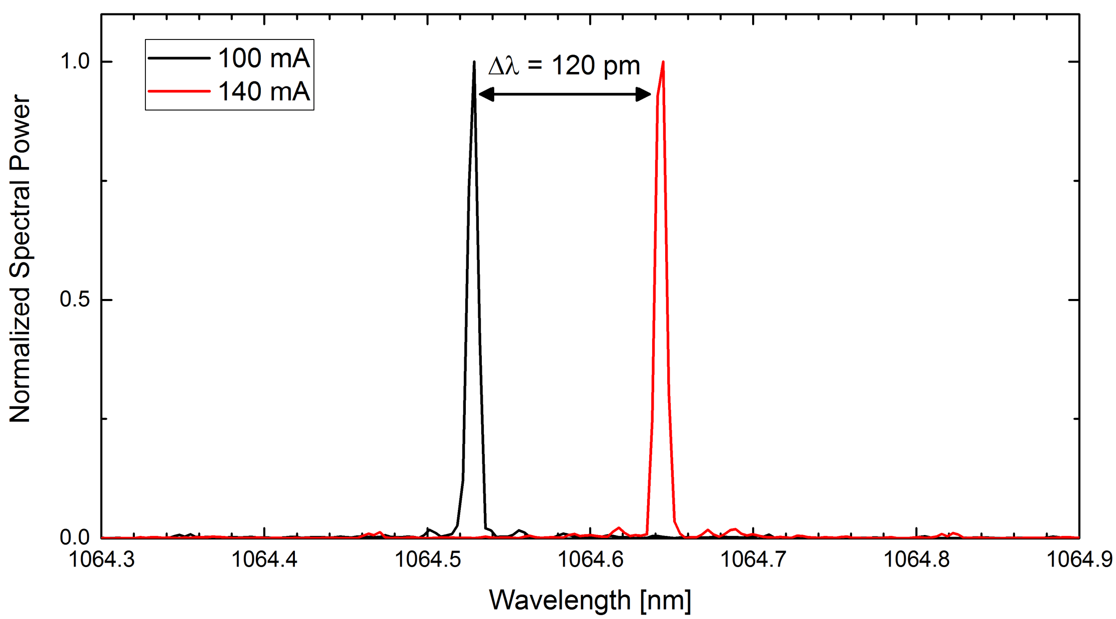

Figure 3. Spectrum of the DFB MOPA in CW operation with 100 mA and 140 mA through the MO. The current through the TA was 4 A and the laser was stabilized at 20°C.

To avoid areas of multimode behavior, the MO modulation was done from 100 mA to 140 mA. The spectrum at these two MO currents can be seen in figure 3.These spectra were measured in CW operation with an optical spectrum analyzer (OSA). The wavelength separation is 120 pm, which was significantly larger than the theoretical full width half maximum (FWHM) of the spectral acceptance bandwidth of the non-linear crystal which is 42 pm.

Figure 4 shows the second harmonic output power versus the near infrared power into the crystal. The infrared power was varied using the half-wave plate before the PBS to avoid changing the laser parameters during the measurements. The figure shows that the SH power nicely follows the quadratic fit as expected.

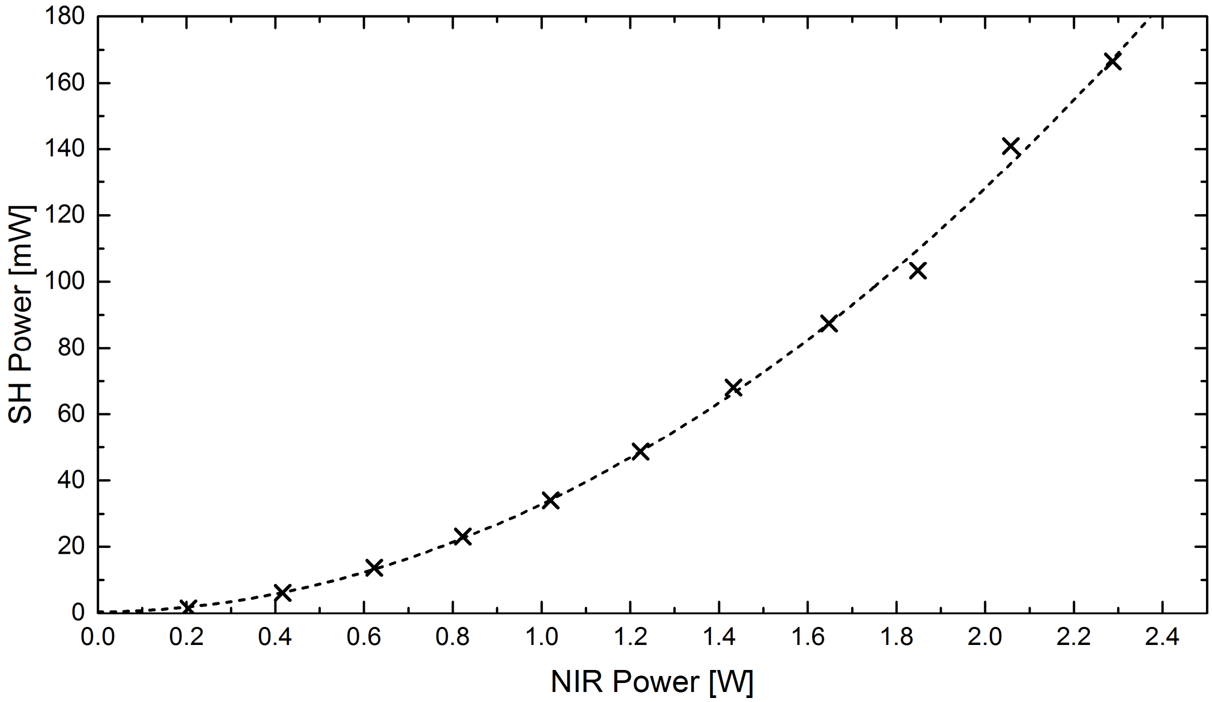

Figure 4. Output second harmonic power as a function of the near infrared power into the crystal. The dotted line is a quadratic fit.

To perform the current modulation a function generator was connected to the analog modulation input on the current supply for the MO. All the pulse trains generated by the function generator were 50% duty cycle square waves. Any change in the laser current will also induce a temperature change within the laser chip. This is usually not an issue if the modulation is performed significantly faster than the temperature time constants of the system. For medical use, each treatment pulse, or pulse train in the case of μ-pulsing, is significantly longer then the temperature timescales of the chip. To show that the small current modulation performed is not affecting the temperature of the system significantly a slow modulation at 0.1 Hz was performed, see figure 5. In this case each pulse was significantly longer than the thermal timescales of the system, i.e. it was a quasi-CW case. From the figure it can be seen that the peak power of the pulses was very stable, indicating that no thermal effects are changing the wavelength throughout the pulse. The modulation depth achieved at 0.1 Hz was 98.2%.

The fastest modulation achieved, where the pulses could still be approximated as square, was 10 kHz, see figure 6. The increased noise in the pulse peak is likely due to wavelength instabilities induced from ringing of the current supply. 10 kHz corresponds well to previously observed modulation bandwidths of this power supply with a 40 mA modulation depth. The modulation depth achieved for 10 kHz was 97.8%. No adjustment of the laser system was needed between the different modulation frequencies. We believe that with a faster power supply it would be possible to modulate this system in the MHz range since the only fundamental limit is the bandwidth of the laser diode. Modulation was also performed at 1 Hz, 10 Hz, 100 Hz and 1 kHz, and very similar results were obtained. The change in the NIR power during modulation was 1.5%, which further indicates that the modulation was done without any significant changes in the thermal load of the laser diode.

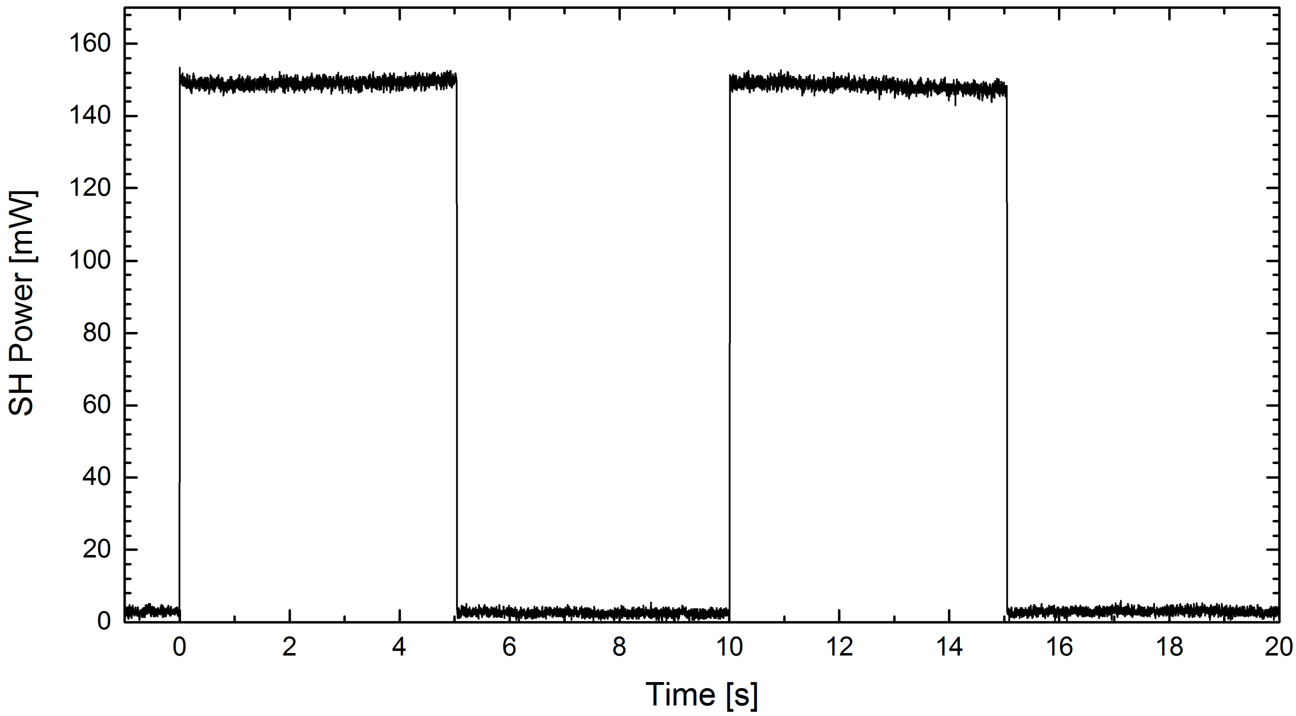

Figure 5. Modulation of the current through the MO from 100 mA to 140 mA with a frequency of 0.1 Hz. The modulation depth achieved was 98.2%.

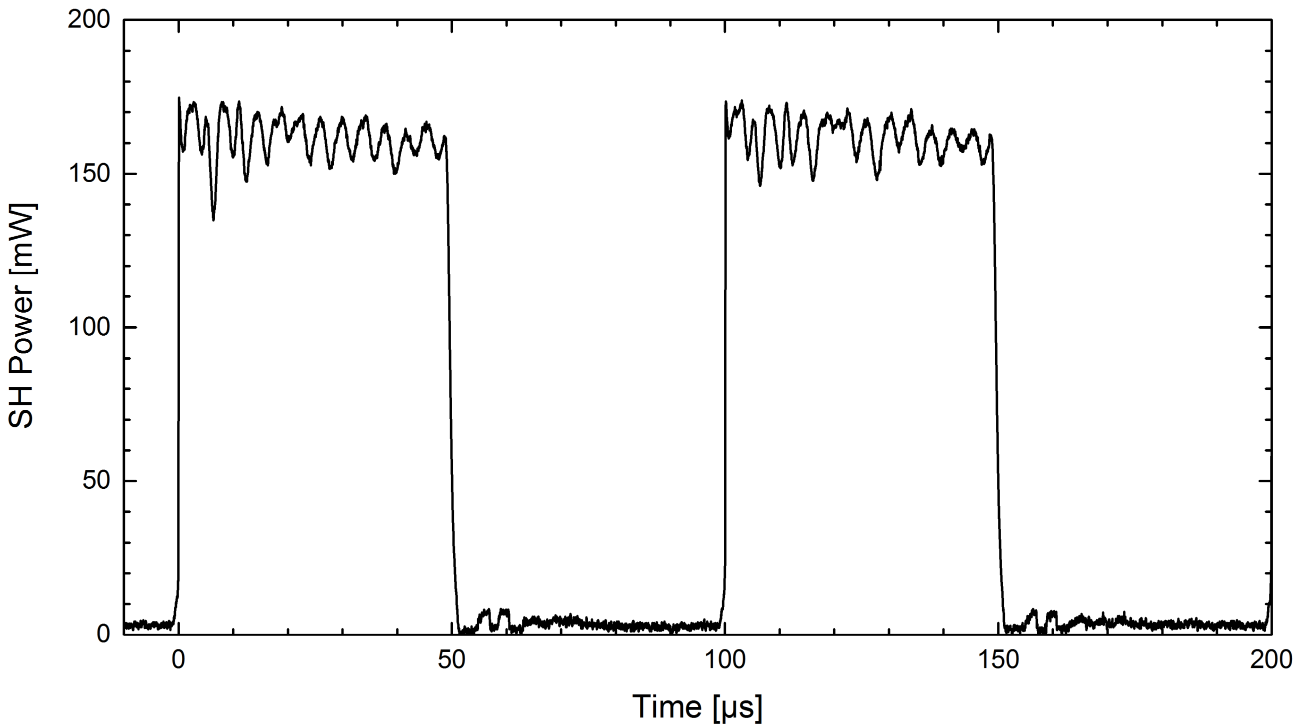

Figure 6. Modulation of the second harmonic output power at 10 kHz. The modulation depth achieved was 97.8 %.

3. CONCLUSION

Modulation of the second harmonic output power from CW and up to 10 kHz has been demonstrated with a modulation depth above 97%. The system was based on single pass frequency doubling of a distributed feedback (DFB) master oscillator power amplifier (MOPA) laser diode. The DFB MOPA is mounted p-side up to allow for separate contacts for the MO and the PA, thereby allowing for wavelength detuning of the laser diode by small adjustments of the current through the DFB section. In CW the laser diode was operated with 140 mA through the MO and 4 A through the PA, and the full modulation depth was achieved by decreasing the current through the MO by 40 mA, thereby changing the CW wavelength 120 pm. The resulting change in near infrared power was 1.5%. The modulation bandwidth was limited by the power supply, while the modulation bandwidth of the laser system was only limited by the bandwidth of the laser diode. The second harmonic output power could be modulated at any frequency without changing any of the operating parameters of the laser head indicating that the system is suitable for pulse on demand applications.

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