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53 ps Pulses at 1.32 μm from a Harmonic Mode-Locked Nd:YAG Laser

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***Abstract*—We have generated 53 ps pulses at 1.32 μm with an average power of 1.5 W by second harmonic mode locking of a CW Nd:YAG laser. The pulse repetition rate can be adjusted to either 100 or 200 MHz by cavity length changes of less than ~10 μm. Short-term fluctuations in pulse intensity were less than ±2 percent.**

INTRODUCTION

ACTIVELY mode-locked continuous-wave Nd:YAG lasers are well known for being reliable sources of continuous trains of sub-100 ps optical pulses at 1.06 and 1.32 μm [1]. They are commonly used as optical pump sources for other lasers, and more recently, in a wide variety of pulse compression experiments [2]. Short, high peak power, infrared pulses are attractive because they can be efficiently frequency doubled to generate even shorter pulses of visible light. Nd:YAG lasers are usually mode locked by either phase (FM) or amplitude (AM) modulators at their fundamental pulse repetition frequency, in which case they generate pulses of less than 100 ps duration with average powers of several watts (1.06 μm) and repetition rates typically around 100 MHz. This fundamental frequency corresponds to the cavity axial mode spacing and yields a pulse train having a 10 ns interpulse spacing.

Most applications of CW mode-locked Nd:YAG lasers readily benefit from shorter pulse durations, and several techniques have been employed to accomplish this. Roskos *et al.* [3], for example, used an intracavity etalon to shorten the pulses of a CW mode-locked Nd:YAG laser to 25 ps pulse duration. Initial theoretical work on mode locking [4] also showed that increasing the modulation frequency was an effective method to shorten pulses. Harmonic mode locking is a technique in which the cavity is modulated at a frequency that is some integer multiple N of the fundamental mode spacing. This technique was first introduced and analyzed by Becker *et al.* [5] in an FM-modulated Nd:YAG laser for values of N up to 5. The theory indicated pulses could be shortened by approximately the square root of N, assuming constant gain, modulation depth, and bandwidth. Becker *et al.* also discovered unique spectral behavior for the $N = 2$ case (hypermodes) that we will discuss later. Stable second harmonic CW mode locking of Nd:YAG at 1.06 μm was first employed by Johnson and Simpson [6], [7] who obtained pulses of less than 50 ps duration, which in turn were frequency doubled and used to synchronously pump subpicosecond dye lasers. Subsequently, it has also been found by others [8], [9] that harmonic mode locking is a simple approach to generate shorter pulses from a mode-locked Nd:YAG laser without significant power or stability penalties compared to fundamental mode locking. Additionally, high-quality fiber-grating pulse compression at 0.53 μm [10] and at 1.06 μm [11] have benefitted from the shorter pulses generated by harmonic mode locking. The physical dimensions of the compressor are considerably reduced, because the optimum fiber length and grating pair separation vary as the square of the input pulse duration [12]. Shorter 1.32 μm pulses could also improve the performance of subpicosecond laser systems using fiber-grating and soliton compressors [13], [14] and fiber-Raman lasers [15], [16].

In this paper, we describe second harmonic mode locking of an Nd:YAG laser at 1.32 μm. Second harmonic mode locking (compared to fundamental mode locking) is especially interesting for the lower gain 1.32 μm line of Nd:YAG because it introduces no additional loss element in the laser cavity. We have achieved pulses of 53 ps FWHM duration with an average power of 1.5 W from a laser that generated 1.7 W when not mode locked. Short-term fluctuations in pulse intensity were less than ±2 percent. This laser also exhibited a unique characteristic in that it was possible to adjust the pulse repetition rate to either 100 or 200 MHz simply by adjusting the cavity length only a few microns. This effect was not predicted by earlier theoretical work, although similar effects have been observed in second harmonic mode-locked Nd:YAG lasers operating at 1.06 μm [6]–[9].

SYSTEM DESCRIPTION

Our system is based on a standard Quantronix 116 CW Nd:YAG laser system with a cavity roundtrip time of 10 ns, and hence, an axial mode spacing of 100 MHz. In this system, the 4 × 79 mm Nd:YAG rod is located at approximately one third of the cavity length from the output coupler. Both the Nd:YAG rod and the acoustooptic

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mode-locking modulator were anti-reflection coated for operation at 1.32 μm. The rear end mirror was concave with a radius of 1 m, and the output coupler was flat with a transmission of 4 percent at 1.32 μm. Both mirrors were coated on wedged substrates to prevent etalon effects. The cavity also included a Brewster plate polarizer and mode limiting aperture (1.8 mm) to ensure TEM_{00} operation. Fundamental mode locking of this cavity is done by driving an (AM) acoustooptic modulator placed near the output end of the cavity by a 50 MHz RF signal. This *driving frequency* yields an effective *mode-locking* (*or modulation*) *frequency* of 100 MHz because each period of the driving waveform provides two high-transmission windows per cavity roundtrip time. To change from fundamental to second harmonic mode locking, a new acoustooptic modulator, optimized for a driving frequency of 100 MHz, was required.

The laser system was designed to be very stable both mechanically and electrically. The entire laser cavity was constructed on a super-Invar breadboard with the standard Quantronix components, except for the mirror mounts which were replaced with Klinger-type SL gimbal mounts. The rear cavity mirror mount was also placed on a precision translation stage equipped with a differential micrometer. The mode locker was driven by a Hewlett-Packard 8640B RF synthesizer followed by a 20 W power amplifier and temperature stabilized to 25°C by an independent cooling system. The exact mode-locker driving frequency was determined by minimizing the reflected RF power from the modulator as a function of frequency. The proper frequency was achieved when maximum power was absorbed by the modulator (i.e., minimum reflection), which occurred at 99.993 MHz for our laser. The cavity length was suitably adjusted to match the fundamental axial mode spacing to this frequency. Thus, the effective mode-locking frequency was 199.986 MHz. The optimum pump lamp current was between 31 and 32 A.

Output pulse parameters were measured by both a high-speed photodetector and an autocorrelator. Pulse train characteristics, as well as rough pulse duration measurements, were made by an ion-bombarded InGaAs photoconductive detector [17] that had a response time of ~35 ps (FWHM). The detector output was measured by a Tektronix S-4 sampling head externally triggered by the RF driving signal for the mode locker. In this way, the relationship of the optical pulse train to the phase of the RF waveform could be observed. Exact pulse duration measurements were made by a standard, background-free scanning autocorrelator with a 1 mm thick $LiIO_3$ crystal as the frequency doubling element.

This laser exhibited operating characteristics not anticipated by earlier theoretical work. Similar effects have also been observed in these lasers at 1.06 μm [6]–[9]. When the cavity length was optimized for the shortest pulse duration and highest stability, the laser could be adjusted to produce pulse trains at either 100 or 200 MHz repetition rates by making cavity length changes of less than 10 μm. Fig. 1(a) shows the unexpected 100 MHz pulse train at an average power of 1.5 W. By slightly perturbing the cavity (e.g., with a cavity length change of a few microns), the laser would also run as in Fig. 1(b), with a 100 MHz pulse train phase shifted by 180° with respect to the RF waveform. Pulse length, average power, and stability were the same in either case, and it appeared that the laser was bistable in regard to these operating regimes. Changing the angle of the mode locker did not appear to control which 100 MHz train the laser preferred, although it could stimulate abrupt changes from one mode to the other. Further detuning of the mode-locker angle only lengthened the pulses and/or defeated mode locking altogether. Fig. 2 shows the autocorrelation trace of the shortest, stable pulses that we observed at 100 MHz. The autocorrelation FWHM was 75 ps, which yields a 53 ps pulse width if we assume a Gaussian pulse shape as is appropriate for these lasers. Short-term stability was on the order of ±2 percent peak to peak.

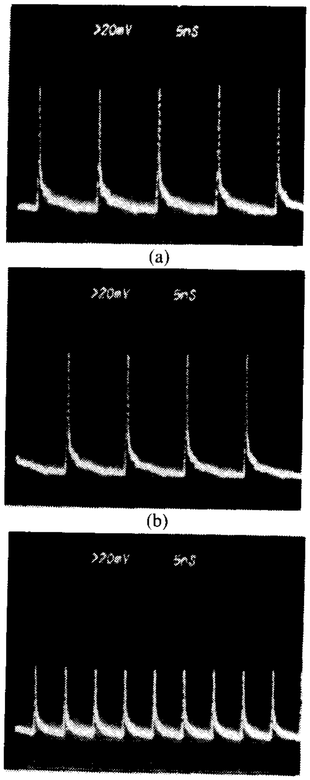

Fig. 1. The three operating regimes of the second harmonic CW mode-locked ND:YAG laser. (a) 100 MHz repetition rate pulse train. (b) Phase shifted 100 MHz pulse train [with respect to (a)]. (c) 200 MHz pulse train.

By detuning the cavity length from optimum by typically less than 10 μm, it was also possible to generate a pulse train at 200 MHz, which is what normally would be expected for mode locking at 200 MHz. Both average power and pulse duration remained essentially the same relative to 100 MHz operation, indicating the peak power of the pulses was reduced by a factor of two. A slight adjustment of the mode-locker angle was sometimes nec-

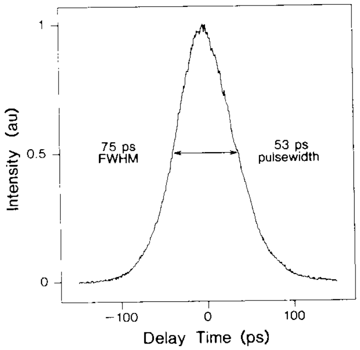

Fig. 2. Autocorrelation trace of 1.32 μm pulses at a 100 MHz pulse repetition rate. Autocorrelation width of 75 ps corresponds to a Gaussian pulse duration of 53 ps. Average output power was 1.5 W.

essary to stabilize the 200 MHz train. It also appeared there was some coupling between alternate pulses, making it seem as though the 200 MHz train was actually composed of two interleaved 100 MHz trains. By adjusting both the cavity length and the mode-locker angle, it was possible to almost continuously vary the pulse height ratio of the interleaved trains. Further detuning of the cavity length (beyond ~10 μm) produced only a 200 MHz train of ever-increasing pulse width and decreasing stability. It was possible to find tuning regimes for either the 100 or 200 MHz trains in which the laser would operate stably for hours.

DISCUSSION

The ability of this laser configuration to generate stable pulse trains at the fundamental repetition rate in spite of the fact that the cavity is actively mode locked at the second harmonic frequency is not currently understood, even though other workers have employed the technique at 1.06 μm to generate pulses (at the fundamental frequency) shorter than would otherwise be possible by fundamental mode-locking techniques [6]–[9]. Previous theoretical and experimental work by Becker *et al.* [5] on harmonic mode locking found the pulse repetition rate was always equal to the *mode-locking* frequency. They also discovered significant spectral changes in the case of $N = 2$ as a function of the position of the laser rod within the cavity. Specifically, with the rod placed at one end of the cavity, they found every other axial mode of the laser spectrum would oscillate, giving rise to a pulse train at the second harmonic frequency. Additionally, either set of alternate modes was found to oscillate (albeit one at a time), each giving rise to a pulse train at the second harmonic frequency. Each set of alternate modes was referred to as a hypermode. However, with the rod placed at the center of the cavity, they found all axial modes in the spectrum would oscillate, but a pulse train at the second harmonic frequency was still emitted. It was speculated that in this case, both hypermodes were only weakly coupled and could oscillate simultaneously with equal amplitudes without being mode locked. (If they were locked, a pulse train at the fundamental frequency would be expected.) Becker *et al.* [5] concluded it was possible for multiple hypermodes to oscillate only if the laser rod were placed at certain critical points within the cavity. These critical points occur at an integral number of $1/N$ cavity lengths from the end of the cavity. For single hypermode operation, they indicated the rod should be located completely outside the critical points.

The effects that we see for second harmonic mode locking at 1.32 μm in our laser are similar to those observed by others at 1.06 μm [6]–[9]. In this case ($N = 2$), the only critical point in the cavity is the center. We find that with the rod positioned ~1/3 of a cavity length from the output coupler, the laser can emit stable trains of pulses at the fundamental frequency $c/2L$, even though mode locking is occurring at the second harmonic $2c/2L$. The effect of rod location on second harmonic mode locking was observed by Heritage [8] using a Quantronix 114 CW Nd:YAG laser with a 3 × 65 mm rod. This early model laser was designed to operate with the rod in the center of the cavity. Utilizing a second harmonic mode locker, Heritage observed that with the rod at the center of the cavity, a pulse train at frequency $2c/2L$ was emitted (in agreement with Becker *et al.* [5]). However, Heritage noted that as the rod was moved away from the critical center location, a pulse train at $c/2L$ was able to form. Further movement of the rod increased the stability of the $c/2L$ train, with the most stable operation occurring at the 1/3 location. This position of the rod satisfies Becker's condition for single hypermode oscillation for $N = 2$, but the $c/2L$ train that is emitted is not a hypermode according to Becker's definition.

We speculate that as the rod is moved away from the center of the cavity, the coupling of the simultaneously oscillating hypermodes increases, and that at the 1/3 cavity location, the two hypermodes experience enhanced coupling that effectively phase locks them. In this case, the axial modes are actually mode locked at the fundamental mode spacing of $c/2L$, which in turn generates a pulse train at the fundamental frequency also. Heritage [8] speculates that the additional coupling mechanism between the interleaved hypermodes could be due to some mechanism (e.g., gain saturation) producing a weak modulation at an odd higher harmonic ($N > 2$). Any odd harmonic modulation would provide a coupling mechanism between the two hypermodes, thus indirectly phase locking all the axial modes. It is expected that the additional coupling, regardless of its source, is weak because small cavity length adjustments can disrupt the process easily. The same behavior has also been observed for an Nd:YAG laser mode locked at the third harmonic [9]. In this case, pulse trains at either the fundamental or the third harmonic frequency could be generated and selected by small cavity length adjustments.

CONCLUSIONS

We have demonstrated second harmonic mode locking as a technique to effectively shorten the pulses of a CW mode-locked Nd : YAG laser at 1.32 μm to 53 ps FWHM without incurring significant power or stability penalties. It was possible to operate the 100 MHz fundamental frequency laser at a repetition rate of either 100 or 200 MHz by making small (< ~10 μm) adjustments to the cavity length. The laser was stable at either repetition rate with a pulse intensity fluctuation of less than ±2 percent. Previous theories did not anticipate these modes of operation, and efforts to understand these mode-locking effects are continuing. Several applications of second harmonic modelocking at 1.06 μm [6], [7], [10], [11] have already demonstrated improved capabilities with significantly shorter pulses, and we anticipate this should also be true at 1.32 μm.

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Martin C. Nuss, for a photograph and biography, see this issue, p. 197.

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