Self-sustained picosecond pulse generation in a GaAlAs laser at an electrically tunable repetition rate by optoelectronic feedback

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We demonstrate that applying optoelectronic feedback to a high-speed, self-pulsing semiconductor laser is an effective and practical means of generating picosecond optical pulses ($\sim$10–20 ps) at a very high repetition rate, between 1 to 5 GHz, which can be electrically tuned. The optical pulses are very stable both on a short term basis with a frequency stability of one part in 10^5, and on the long term basis as a result of the absence of critical optical alignment. This laser system is potentially very useful in high-speed electro-optic signal processing, optical multiplexing, or laser ranging.

Picosecond pulse generation from semiconductor lasers at high repetition rate is generally accomplished by two different means: mode locking (either passive or active) or direct electrical excitation. The shortest pulses (below 1 ps) were generated by a passively mode-locked GaAlAs laser,[1] while active mode locking produces somewhat longer optical pulses ($\sim$10–20 ps).[2] The pulse repetition rate of the mode-locked laser is determined by the length of the external cavity and cannot be varied easily. The rather critical optical alignment necessary for operating the mode-locked laser in an external cavity is a disadvantage in practical applications, where mechanical vibration and/or temperature variation may be encountered. The desire for continuously variable pulse repetition rate and simple or no optical alignment prompted development of a second means of picosecond pulse generation: by directly pumping the laser with intense, short electrical pulses[3,4] or by large-amplitude sinusoidal current modulation.[5–7] Optical pulses generated by such means have pulse widths in the vicinity of 15–35 ps. This scheme requires an external, fairly high power ($\sim$1 W) rf source for exciting the laser. An alternative scheme is to induce intensity pulsation in semiconductor lasers by optoelectronic feedback. In one demonstration,[8] detector limited pulses of 70 ps have been generated by this method, while in a separate instance sinusoidal or square wave modulation in the optical output is observed.[9] It is not clear what factors underlie the differences in these results. However, one sure way of generating short optical pulses is to apply optoelectronic feedback to a self-pulsing laser, shown schematically in Fig. 1(a), as first demonstrated more than a decade ago by Paoli and Ripper.[10] The characteristics of the lasers used in that early experiment were less than satisfactory by today's standards, and the exact pulse width was not measured. In this letter, we will show that by using a state-of-the art high-speed laser in the optoelectronic feedback configuration

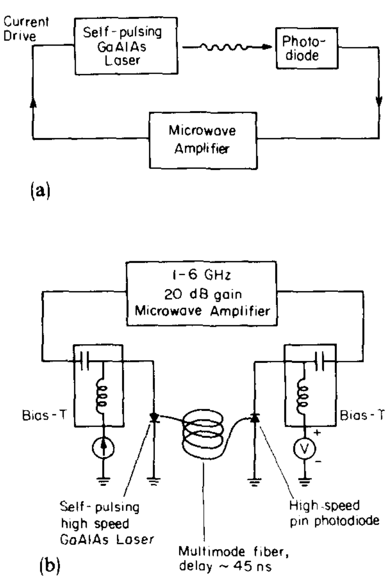

FIG. 1. (a) Schematic diagram of the optoelectronic feedback configuration; (b) experimental arrangement used in this work.

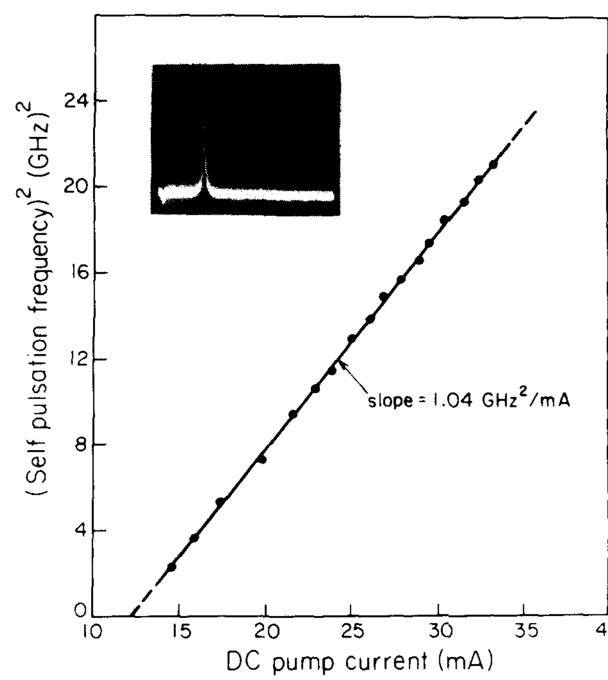

FIG. 2. Variation of the self-pulsation frequency with pump current. Inset shows rf spectrum of the self-pulsation, Hor. 1.7–3.5 GHz, ver. 5 dB/div.

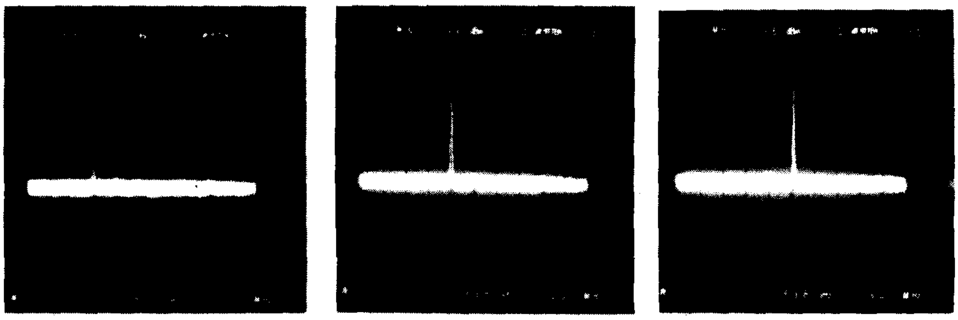

FIG. 3. rf spectrum of the self-pulsation with the laser under optoelectronic feedback. The three successive pictures show the frequency jumping as the pump current is varied from 19.02 mA (left) to 19.1 mA (middle) and 19.19 mA (right). Hor. 50 MHz/div. center at 1.938 MHz, ver. 10 dB/div.

shown in Fig. 1(b), highly stable optical pulses (with a frequency jitter of < 30 kHz) of pulse widths between 10 to 20 ps can be generated, with a very high repetition rate from 1–5 GHz which can be electrically tuned. This scheme has the advantage of obviating the need for any external rf drive and sensitive optical alignment. The optical pulse width thus obtained is not as short as that in passive mode locking, but is among the shortest that have ever been generated in a semiconductor laser otherwise.

The lasers used in this experiment were similar to the high-speed GaAlAs lasers reported recently,[11] which possess the highest direct modulation speed reported thus far. Self-pulsation was induced in these otherwise well-behaved lasers by momentarily operating the lasers beyond the catastrophic damage level. It must be emphasized here that it is *not* necessary for one to induce damage to a laser for it to self-pulse; a highly reliable way of accomplishing the task is by a double contact laser structure reported previously.[12] The rf spectrum of the intensity pulsation of the laser, as detected by a fast pin photodiode, is shown in the inset of Fig. 2. The frequency f of pulsation varies with the pump current i following a $\sqrt{i - i_{th}}$ dependence as in conventional relaxation oscillation in lasers, as shown in Fig. 2. The intensity spectral width of the pulsation, as observed on the microwave spectrum analyzer, is ~ 4 MHz. This value changes only slightly at different pulsation frequencies.

Next, the laser is operated in an arrangement shown in Fig. 1(b). The laser and the pin detector are mounted in standard fiber-pigtail high-frequency packages, and the optical fiber (multimode, graded index) connecting the laser and pin detector provides a delay of ~ 15 ns. The dc photocurrent from the pin detector was 475 μA when the laser emits an average power of 2.5 mW fact, indicating an overall coupling efficiency of 42% from the laser to the pin detector. The rf output from the high-speed pin detector is amplified by a 20-dB gain microwave amplifier in the range of 1–6 GHz. On completion of the feedback loop, the rf spectrum of the intensity pulsation changes from that shown in Fig. 2(a) to those shown in Fig. 3. The intensity output from the laser now pulsates, with a much reduced linewidth, at an integral multiple of f_0 which is closest to the "natural" self-pulsation frequency of the solitary laser (without optoelectronic feedback), where f_0 is the inverse of the total delay in the feedback loop, ~ 20 ns in this case. This result can be explained by interpreting the self-pulsing laser as a device with a very high gain in a narrow frequency band around the self-pulsing frequency, and hence oscillation commences at the integral multiple of f_0 which has the highest open-loop gain. As the natural self-pulsing frequency is tuned by varying the pump current, the pulsation frequency jumps from one integral multiple of f_0 to the next, as shown in Fig. 3. The jumps occur very abruptly, and in between jumps the pulsation spectrum remains single frequency as those shown in Fig. 3, and does not change in response to the varying current. There is no observable hysterectic effect as the current is ramped upward and downward. The pulsation repetition rate can be step tuned from 1.2 to 4.5 GHz by varying the pump current, the lower limit being set by the minimum bias current for the laser to self-pulse, while the upper limit is imposed by minimization of further damage to the laser. The rf "sidebands" (barely visible in Fig. 3) are > 40 dB below the main line, whose existence corresponds to a small undulation in the amplitude of the optical pulses with a period equal to $1/f_0$.

The rf spectral line shown in Fig. 3 is only the fundamental of the many harmonics observed on the microwave spectrum analyzer. This is a direct indication that the optical output is indeed pulselike. The amplitude of the higher harmonics does not differ from the calibrated frequency response of the pin detector (using a mode-locked dye laser for the calibration) by more than ± 0.5 dB up to 15 GHz. The exact optical pulse width was measured by a standard optical doubling autocorrelation technique using $LiIO_3$ as the nonlinear medium. During these measurements, the loop gain is fixed at a value of 7. Assuming a Gaussian pulse shape, the measured pulse width is shown in Fig. 4, as a function of the pulsation repetition rate. The pulse width varies between 20 to 12 ps within the repetition rate tuning range. In contrast, when the optoelectronic loop is opened, the pulse width of the self-pulsing laser is ~ 57 ps.

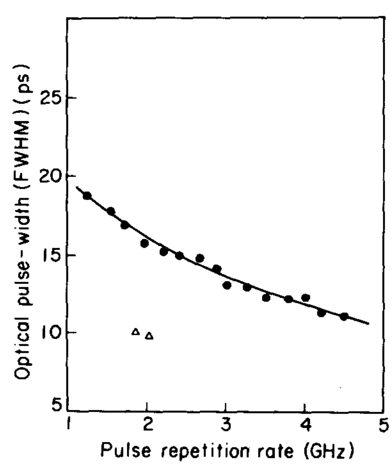

FIG. 4. Measured optical pulse width vs pulse repetition rate at a loop gain of 7. The triangular data points are obtained with a loop gain of 65.

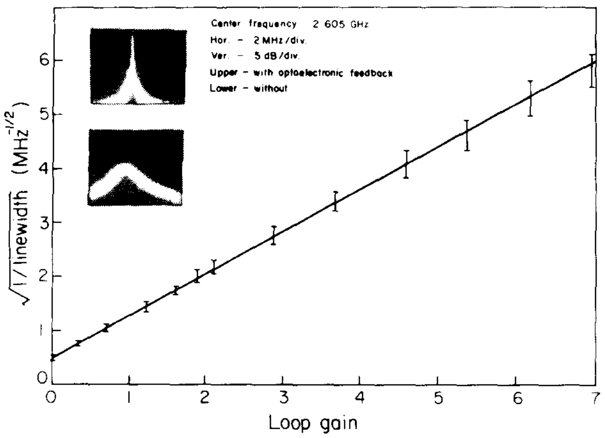

FIG. 5. Variation of rf linewidth of the pulsation with loop gain. The inset shows the rf spectrum with (top) and without (bottom) optoelectronic feedback.

Next, the wideband microwave amplifier (1–6 GHz, 20 dB gain) is replaced by a high gain (39.5 dB) narrowband amplifier (1.8–2 GHz) which produces a loop gain of 65. Under this increased loop gain, the measured pulse width falls below 10 ps, the shortest being 9.5 ps at a pulse repetition rate of ~ 2 GHz (shown by the triangles in Fig. 4).

The short term stability of the optical pulses is directly related to the linewidth of the rf spectral lines as those shown in Fig. 3. An expanded view of the rf line is shown in upper inset in Fig. 5, as compared to that of a solitary self-pulsing laser (without optoelectronic feedback) as shown in the lower inset in Fig. 5. The variation of the linewidth with open loop gain is shown in Fig. 5. It is empirically deduced from experimental data that the linewidth varies with the inverse power gain of the open loop. A minimum linewidth of 27 kHz was obtained with an open loop gain of 7. (The close loop gain is, of course, less than 1, the saturation being, most likely, due to the loop amplifier). The data shown in Fig. 5 are obtained at a pulse repetition rate of 2.6 GHz. This result corresponds to a frequency stability of one part in 10^5. The long term stability can be extremely well maintained, since the output power from the laser is feedback stablized (using a separate, slow monitor photodiode which is an integral part of the high-frequency package) and the fiber-pigtail package is very rugged and stable.

In conclusion, we have demonstrated that applying optoelectronic feedback to a high-speed self-pulsing semiconductor laser is an effective and practical means of generating picosecond optical pulses at very high repetition rates, which can be electrically tuned. This laser system may prove useful in high-speed electro-optic signal processing, optical multiplexing, or laser ranging, where subpicosecond pulses are not absolutely necessary and high repetition rate and ruggedness are highly desirable.

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