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Picosecond optical pulse generation at gigahertz rates by direct modulation of a semiconductor laser

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We report the generation of picosecond pulses by the direct modulation of a buried heterostructure GaAlAs diode laser. Pulse width of 28 ps is achieved at a repetition frequency of 2.5 GHz. Pulse width dependence on the experimental parameters is described.

PACS numbers: 42.80.Ks, 42.55.Px

A promising approach to increase the bit rate in pulse code modulation (CM) of semiconductor lasers for fiber optic communication is to multiplex trains of ultrashort optical pulses. Experimental[1-5] and theoretical[6,7] efforts directed toward the modelocking of semiconductor lasers to produce picosecond pulses have been reported. It is believed that model locking will achieve the shortest pulses; but the use of an external cavity requires careful alignment and good vibration isolation. Other techniques to produce ultrashort optical pulses from semiconductor lasers have been investigated.[8-14] A simple scheme involves the direct modulation of a laser diode with a large sinusoidal signal or short current pulses. Even though the pulses are significantly broader than the shortest obtained by passive model locking,[5] the simplicity of this method makes it important to be explored further. It is especially desirable to push the generation of these short pulses to high repetition rates to investigate the speed limit of the laser diodes and also to make this scheme useful for multiplexing.

There are two schemes to produce short pulses under the direct modulation method. One scheme involves the biasing of the laser diode high above threshold to increase its modulation bandwidth and then exciting the laser with current pulses. Experiments[13,14] employing this technique have achieved 85-ps pulses and PCM word generation at 8 Gbit/s. The high dc bias eliminates pattern effect but causes the laser pulses to be superimposed on a constant background optical intensity. The second scheme, known as gain switching, consists of pumping the laser diode with a strong sinusoidal[8] or ultrashort pulse[9,10] current with zero or below-threshold dc bias. The gain and hence the optical intensity inside the laser cavity are turned on and off very rapidly. The resulting optical pulse widths, typically on the order of a few cavity round trip time, are determined by the carrier-photon interaction as seen in the relaxation oscillation phenomenon. Pulse widths of 25 ps at 0.7 kHz,[9] 35 ps at 300 MHz,[8] and 40 ps at 500 MHz,[10] have been achieved. Because of the small dc bias, high peak curent is needed but no background light exists between pulses. Gain switching may therefore be better for optical multiplexing of pulses generated at constant rate.

In this letter we wish to report the observation of picosecond pulse generation from a laser diode at gigahertz rates by the gain switching method. The dependence of the pulse width and peak pulse power on the experimental parameters is described. Because of the use of a laser diode with a threshold current much lower than those in the earlier works,[8,10] we are able to drive the laser with moderate current levels with no dc bias. Using the standard autocorrelation technique, we measure pulse widths on the order of several cavity round trip time with a repetition frequency ranging from 500 MHz to 2.5 GHz. The driving signal is a half-sine-wave, derived from a rf power generator. This setup allows us to change the frequency and magnitude of the pumping current more easily than those of the step recovery diode impulse generator used in Ref. 10. As a result, pulse width and peak power variations can be measured as the experimental parameters are changed.

The semiconductor laser used in our experiment is a buried heterostructure GaAlAs laser diode[15] mounted on a heat sink at room temperature. Its cw threshold is 21 mA and the emission wavelength is 0.812 μm. It is a single lateral mode laser with a symmetrical far-field angular speed of 40° in each plane. At threshold, several longitudinal modes oscillate simultaneously with a $\Delta\lambda = 2.7$ Å between adjacent modes. At 5 mA above threshold, the emission spectrum shows a single dominant longitudinal mode. The laser is mounted at the end of a microstrip and in series with a 30-Ω chip resistor. A high-speed Schottky-barrier diode is connected with reverse polarity in parallel to the laser diode to protect the laser from excessive reverse voltages. The 30-Ω resistor is used to match the laser to a 50-Ω transmission line. A swept-frequency reflection measurement with a network analyzer showed that the ratio of reflected to incident rf power is at the most -5 dB between 100 MHz and 4 GHz.

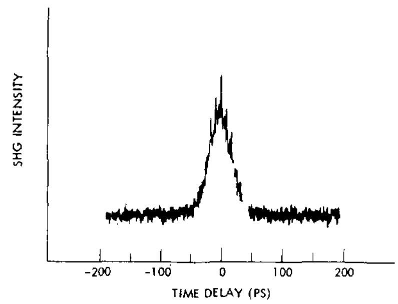

FIG. 1. SHG autocorrelation measurement of ultrashort diode laser pulses. The laser is not biased and is driven by 150 mA peak current at 2.5 GHz. Peak optical power is 10.2 mW. The pulse width (FWHM) is 28 ps, assuming a Gaussian profile.

The highest repetition frequency at which picosecond pulses were generated by gain switching was 500 MHz.[10] We therefore investigated the frequency range above 500 MHz. The laser is driven, at zero dc bias, by sinusoidal signals from 500 MHz to 2.5 GHz. Because of the Schottky barrier diode that is connected in parallel with the laser diode, the current flows through the laser in only one-half of each cycle. The laser excitation current is expected to behave as the positive portion of a sinusoid, with a full width at half-maximum (FWHM) of 133 ps at 2.5 GHz.

The optical output is collimated by a 20×, 0.35 NA microscope objective and monitored by a high-speed photodiode.[16] Detector limited pulses 70 ps FWHM are observed on a sampling oscilloscope. The actual pulse width is measured by the usual nonlinear autocorrelation technique using type I collinear phase-matched second harmonic generation (SHG) in $LiIO_3$. Figure 1 shows an autocorrelation trace of the optical output pulses at 2.5 GHz. The autocorrelation shows the usual structures of coherent spikes, a pedestal and a uniform background. The pedestal has a FWHM of 40 ps. Assuming a Gaussian pulse shape, we estimate the pulse width (FWHM) to be 28 ps. The coherent spikes, which indicate the excitation of more than one longitudinal mode, are separated by 8.8 ps, the round-trip time of a 260 μm long laser cavity. This agrees approximately with the 244 μm, obtained from the 2.7-Å longitudinal mode spacing observed in the emission spectrum. The two beams in the autocorrelation arrangement are of equal intensity. One beam is chopped at 27 Hz; and the second harmonic intensity is detected by a photomultiplier followed by a lock-in amplifier. The theoretical contrast ratio of the central coherent peak, the pedestal and the background is 5:3:1. The measured ratio is 4:3:1. The full height of the central spike is not reached because of the measurement system's limited resolution. However, the measurement shows that there is negligible background light between the pulses.

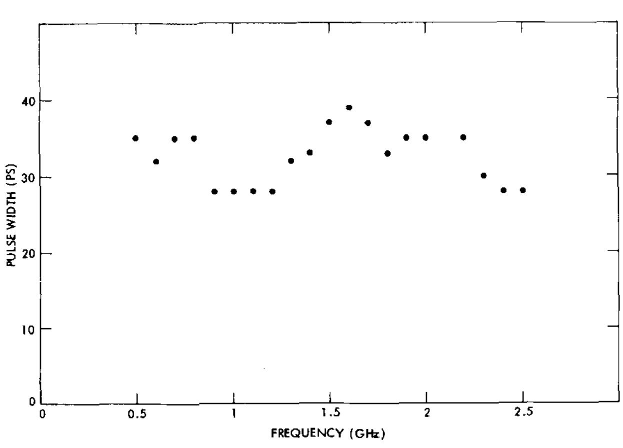

FIG. 2. Pulse widths vs drive frequency calculated from SHG autocorrelation measurements assuming Gaussian profiles.

TABLE I. Pulse widths at 1.3 GHz, 98-mA peak current for five different dc bias levels.

dc bias (mA)	Average optical power (mW)	Peak optical power (mW)	Pulse width (ps)
0	0.55	11.4	35
1	0.68	14	35
2	0.76	16.2	34
3	0.86	20.7	30
4	0.95	24.5	28

In Fig. 2, we plot the FWHM pulse widths, calculated as above from SHG autocorrelation measurements assuming Gaussian pulse shapes, as a function of rf frequency at zero dc bias for the laser. The peak current is adjusted at all frequencies to maintain a same average optical power of 0.76 mW when measured behind the microscope objective. This optical power level ensures a safe operation of the laser diode. The peak current ranges from 3.5 to 10 times the cw threshold current. The error in the pulse-width measurement is $\pm$ 10%. Figure 2 shows that the pulse width does not change much, typically on the order of three to four times the cavity round-trip time. We note that there are two variables in these data, namely, the driving frequency and the peak current. The variation of the pulse width will, in general, depend on both variables. At the low-frequency end (ca. ~ 500 MHz), some ringing after the optical pulse is seen on the oscilloscope. At the high-frequency end ($\geqslant$2.3 GHz), the laser output power decreases rapidly with time (50% power drop in 1 min) when the rf power is turned on. An increase in laser threshold (15%) is also observed. It appears to be a thermal effect because the threshold returns to its original value several minutes after the rf power is turned off. This problem is alleviated when additional cooling by a fan is provided at the driving frequencies from 2.3 to 2.5 GHz. We believe that with a better heat sink, still higher repetition rates, > 2.5 GHz can be achieved. Pulse width decreases and peak power increases with increasing rf power and dc bias

TABLE II. Pulse widths at 1.3 GHz, zero dc bias for six different peak currents.

Peak current (mA)	Average optical power (mW)	Peak optical power(mW)	Pulse width (ps)
91	0.24	4.3	40
95	0.29	5	42
98	0.51	11.5	32
100	0.69	16.1	31
105	0.82	21.2	28
111	1	25.8	28

level. This behavior agrees with our theoretical analysis using the coupled nonlinear rate equations. Tables I and II list the pulse widths and the calculated peak powers at a fixed repetition frequency (1.3 GHz), as a function of the dc bias and the peak current. At a constant rf power and dc bias, the peak optical power decreases with increasing rf frequency. Continuing experimental and theoretical efforts are in progress to understand the pulse-width dependence on the various parameters.

In conclusion, we have obtained 28-ps pulses at 2.5 GHz by direct modulation of a buried heterostructure laser diode. This technique promises to be a practical way to attain high bit rate pulse code modulation for fiber optic communication.

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A classical electron cyclotron quasioptical maser

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In this work a new classical electron cyclotron maser oscillator is proposed and analyzed. The configuration utilizes an open-resonator cavity containing a gyrating electron beam, which translates along an external magnetic field directed transverse to the axis of symmetry of the resonator. The nonlinear interaction between the electrons and resonator fields have been analyzed, and an expression for the steady-state efficiency is obtained. For a uniform, external magnetic field our example shows that total efficiencies in excess of 30% can be realized, while appropriately contouring the field increases the efficiency to $\sim 45\%$.

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In this letter we propose and analyze a new electron cyclotron maser oscillator configuration, which utilizes an open resonator cavity. This quasioptical cyclotron maser has the unique potential for becoming a new type of coherent radiation source. In principle, the device is capable of generating coherent radiation in the millimeter to submillimeter regime, at power levels in excess of magawatts with efficiencies exceeding 40%. The basic structure consists of an open resonator containing a beam of electrons gyrating about, as well as streaming parallel to, an applied magnetic field. The magnetic field is directed transverse to the axis of the open resonator, which consists of two or more appropriately curved mirrors.

The configuration we propose involves a beam-wave interaction, similar to that of the conventional electron cyclotron maser,[1–10] and accordingly it shares the advantages of that interaction. Some of them are (i) high operating efficiency, of the order of 40%, (ii) moderately low electron beam energy requirements. e.g., 10–100 keV, even though the wave-particle interaction mechanism is due to relativistic effects, and (iii) high operating frequency, limited by the external magnetic field.

In addition, the introduction of the open resonator results in a number of further advantages which eliminate the limitations associated with closed cavities. Some of these advantages are (i) natural selection of the fundamental transverse mode, since higher-order modes suffer from diffraction losses and have substantially lower Q's, (ii) extremely high operating power levels, in excess of MW's due to the large interaction volume, (iii) low beam power density requirements (but large overall beam power, in view of the large interaction volume), thus removing the usual limitations on beam power imposed by space charge effects, and (iv) an operating frequency independent of the dimensions of the structure.

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