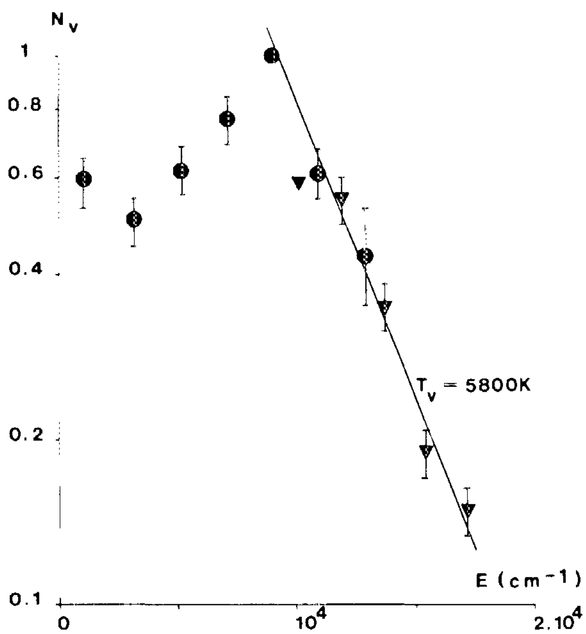


FIG. 2. Normalized CN vibrational distribution up to $v' = 4$ ($A$ state) using Arnold's Einstein coefficients for the $A$ state, and Danylewych's[17] for the $X$ state (He: 16.6 mmol/s, CO: 0.11 mmol/s, $N_2O$: 0.186 mmol/s, injected power in the discharge: 200 W (●) $X$ state; (▼) $A$ state.

fraction. Furthermore, one can see from Fig. 2 that there is a total population inversion between levels ($A$, $v' = 0$) and ($X$, $v'' = 1$). The C + $N_2O$ reaction could then be a viable candidate for a chemical laser system.

In conclusion, we have shown that levels ($X$, $v'' = 4$–6) and ($A$, $v' = 1$–4) of the CN radical were in a pseudoequilibrium. 30% of the radicals are in the $A$ state. A total population inversion has been observed between levels ($A$, $v' = 0$) and ($X$, $v' = 1$).

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# Measurement of picosecond semiconductor laser pulse duration with internally generated second harmonic emission

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We demonstrate a simple practical technique for the measurement of the duration of picosecond semiconductor laser pulses using the internally generated second harmonic emission accompanying the laser output. The pulse duration is determined by the ratio of the conversion efficiencies of the second harmonic emission generated by the picosecond pulses and by the cw emission or other pulsed emission whose duration can be accurately measured. The pulse duration thus measured is in close agreement with that determined by the nonlinear intensity autocorrelation technique.

Ultrashort optical pulse generation with semiconductor lasers is currently of interest for such applications as high bit rate optical communications and very fast data processing. In the picosecond regime, the most commonly used technique of pulse duration measurement is the nonlinear intensity autocorrelation technique involving phase-matched second harmonic generation in a nonlinear optical crystal, such as a $LiIO_3$ crystal.

In this letter, we describe a simple and accurate technique for measurement of picosecond semiconductor laser pulse duration using the internally generated second harmonic emission accompanying the laser output. The picosecond pulse duration is determined by the ratio of the conversion efficiencies of the second harmonic emission generated by the picosecond pulses and by the cw emission or other pulsed emission whose durations can be accurately measured by photodetectors. The apparatus consists of a photodiode for measuring the fundamental laser power, a photomultiplier for measuring the second harmonic power, and appropriate filters. No critical optical alignment is needed. The pulse duration thus measured is in close agreement with that determined by the nonlinear intensity autocorrelation technique. The simplicity and accuracy make this technique very useful for practical applications.

There have been several reports on the properties of the second harmonic emission in GaAs (Ref. 1) and InGaAsP (Ref. 2) lasers. In conventional semiconductor lasers, the epitaxial layers are grown in the (100) plane and the cleaved facets are in the (110) plane. The symmetry of the laser materials requires that the TE laser emission, the normal operating mode, generates second harmonic emission, polarized in the direction normal to the junction plane, while the TM laser emission generates no second harmonic emission. Since the power of the second harmonic emission is proportional to the square of the peak laser power, at a given average laser power the second harmonic emission is stronger when the laser is operated pulsed than cw. By comparing the power of the second harmonic emission generated by the picosecond pulses with that generated by the reference signal which can be the cw emission or other pulsed emission with known pulse duration, the duration of the picosecond pulses can be determined. Assuming that the picosecond laser pulses have a pulse shape $I(t)$ and repetition rate $R$, the average laser power is given by $\overline{P}_{\omega} = R \int_{-\infty}^{\infty} I(t)dt$ and the average second harmonic power is given by $\overline{P}_{2\omega} = \eta R \int_{-\infty}^{\infty} I^2(t)dt$, where $\eta$ is the conversion efficiency. By direct integration, it can be shown that the FWHM pulse duration $\Delta t_{\rm FWHM}$ of the picosecond pulses is given by

$$\Delta t_{\rm FWHM} = A \frac{D_{\rm reference}(\overline{P}_{2\omega}/\overline{P}^{\,2}_{\omega})_{\rm reference}}{R\,(\overline{P}_{2\omega}/\overline{P}^{\,2}_{\omega})_{\rm picosecond\ pulses}}, \qquad (1)$$

where $A$, a shape-dependent factor, is 0.66 for Gaussian pulse shape and 0.35 for symmetric two-sided exponential pulse shape, $D_{\rm reference}$ is the duty cycle of the cw or the rectangular-shaped reference signals, and $(\overline{P}_{2\omega}/\overline{P}^{\,2}_{\omega})_{\rm reference}$ and $(\overline{P}_{2\omega}/\overline{P}^{\,2}_{\omega})_{\rm picosecond}$ are the ratios of the average second harmonic power and the square of the fundamental power of the reference signal and the picosecond pulses, respectively. Equation (1) is derived under the assumptions that the efficiencies of second harmonic generation for the reference signal and the picosecond pulses are independent of the lasing spectra and that the laser does not emit significant spontaneous emission background associated with the picosecond pulses. Conditions deviating from these assumptions may cause errors and will be discussed later.

The lasers used for this study are InGaAsP/InP planar active layer buried heterostructure lasers emitting at 1.3 $\mu$m wavelength. The threshold currents are typically 20 mA. The picosecond laser pulses are generated by driving the lasers directly, without bias, with 100 MHz repetition rate, 80 ps duration electrical pulses from a Comb generator. For the reference signals, we operate the laser in the cw mode and in square pulses with various pulse durations ranging from 5 to 100 ns. The durations of the reference pulses can be accurately measured using a high-speed photodiode and a sampling oscilloscope. The average power of the TE laser emission is detected by a Ge *pin* photodiode. The average power of the second harmonic emission is detected by a photomultiplier. The photocurrents from both detectors are displayed on multimeters. A short pass filter is placed in front of the photomultiplier to block the laser light because the photomultiplier still has residual response to the intense 1.3-$\mu$m wavelength emission. Figure 1 shows the average second harmonic power versus the average fundamental power plotted on a log-log scale for (a) the cw emission, (b) 40 ns pulse duration, 4% duty cycle reference signals, and (c) 10 ns pulse duration, 1% duty cycle reference signals. The solid lines are the slope-two lines drawn through the data points. The nearly perfect slope-two relationship between the second harmonic and the fundamental powers over a wide range of power reflects very good laser beam stability essential for the accuracy of the pulse duration measurement. Point $D$ corresponds to the 100 MHz repetition rate, picosecond pulses whose durations are to be determined. Using Eq. (1) and the values of $(\overline{P}_{2\omega}/\overline{P}^{\,2}_{\omega})_{\rm reference}$ and $(\overline{P}_{2\omega}/\overline{P}^{\,2}_{\omega})_{\rm picosecond}$ deduced from Fig. 1, the duration $\Delta t_{\rm FWHM}$ is 23.5 ps based on line (a), 20 ps based on line (b), and 21 ps based on line (c) assuming Gaussian pulse shape, and 12.3, 10.5, and 11.1 ps, respectively, assuming symmetric two-sided exponential pulse shape. To check the accuracy of this technique, we have measured the pulse duration using the nonlinear intensity autocorrelation technique. The autocorrelation trace is shown in Fig. 2. The deconvoluted pulse duration is 22 ps for Gaussian pulse shape and 12.8 ps for symmetric two-sided exponential pulse shape. The values determined by the inter-

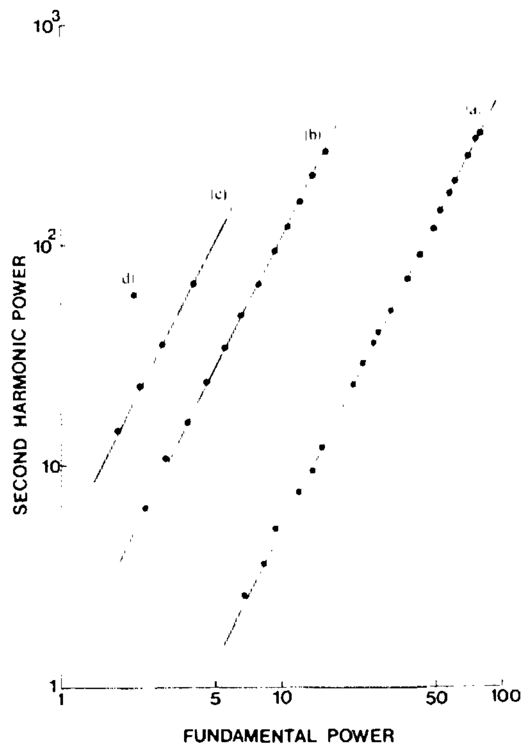


FIG. 1. Second harmonic power vs fundamental power of an InGaAsP/InP laser under (a) cw, (b) 40 ns duration, 4% duty cycle, (c) 10 ns duration, 1% duty cycle, and (d) 100 MHz repetition rate picosecond pulsed operations.

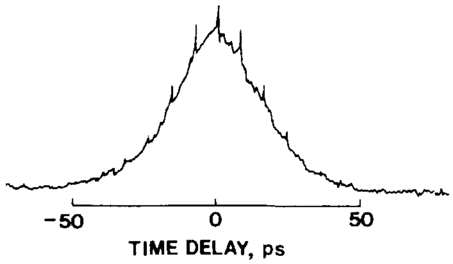


FIG. 2. Autocorrelation trace of the picosecond pulses.

nal second harmonic emission are in close agreement with that determined by the autocorrelation technique, assuming the same pulse shape.

We note that in order to achieve high accuracy, background subtraction for the fundamental power and appropriate choice of the reference signal may be necessary. In the present study, the $P_\omega$ for the picosecond pulses is the total measured power without background subtraction because the ratio between the energy contained in the pulses and the background is very high ($>20{:}1$). This high contrast ratio is attributed to the index-guided laser structure and low threshold current. The ratio, however, is much lower for pulses generated from the gain-guided lasers with high threshold current.[3] In those cases, the background energy needs to be subtracted from $\overline{P}_\omega$.

The efficiency of second harmonic generation depends on the number of longitudinal modes in the lasing spectra. If the fundamental power $I$ is equally distributed over $N$ longitudinal modes, the second harmonic power is proportional to $(2 - N^{-1})I^2$.[4] Errors could be introduced if the reference signal has one longitudinal mode and the picosecond pulses have many longitudinal modes. The sensitivity to the choice of the reference signal disappears when $N = 1$ or $N \gg 1$. The $N = 1$ case corresponds to the dynamic single mode lasers, such as the distributed feedback lasers, whose lasing spectra are always single mode. The InGaAsP/InP lasers used for this study belong to the $N \gg 1$ case. The lasing spectra contain four modes under cw operation at 5 mW, and over 10 modes under the picosecond pulsed operation. In general, if the laser operates in many longitudinal modes under picosecond pulsed operation, the use of multimode reference signals, such as square pulses with durations in the nanosecond range, can reduce potential errors caused by the spectral dependence of the second harmonic generation efficiency.

In conclusion, we have demonstrated a simple technique for the measurement of the duration of picosecond optical pulses of semiconductor lasers, using internal second harmonic generation. The pulse duration determined by this technique is in close agreement with that measured by the intensity autocorrelation technique.


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# Highly anisotropic optical properties of single quantum well waveguides


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The first measurements of the linear and nonlinear anisotropic absorption of light propagating along the plane of a single quantum well are reported and discussed in terms of the structure of the valence band in ultrathin semiconductor layers. Nonlinear optical effects are compared to those of multiple layer structures and to recent theory.


An interesting property of quantum well structures is that, due to the two-dimensional confinement, excitonic effects are greatly enhanced compared to those of bulk material. As a result of this enhancement excitonic absorption has been observed at room temperature in GaAs multiple quantum well structures (MQWS)[1] and more recently in InGaAs/InAlAs MQWS.[2] Room-temperature excitonic resonances in GaAs MQWS's have already been used for high-speed modulators,[3] optical switches,[4] and mode locking of diode lasers.[5] An additional effect due to the reduced dimensionality is that the band-to-band transitions are predicted to be anisotropic for light propagating parallel to the plane of