Balanced detection technique to measure small changes in transmission

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A novel technique to measure changes in optical transmission of better than 10^{-3} with time resolution of better than 10 ns is discussed. The photocurrent from two photodiodes is subtracted with a balanced detection circuit to eliminate the common signal; carrier-induced change in absorption for a semiconductor single quantum well produces a large differential signal.

Introduction

Widespread use of semiconductor single quantum well (SQW) layers as the gain medium in injection laser diodes has created the need to understand the optical and electrical properties of SQW's. Generally, to gauge the quality of SQW material for laser applications one would measure the carrier lifetime as well as the photoluminescent efficiency. The former gives information on carrier transport, whereas the latter gives a measure of defect density. Because of their nonlinear optical properties, quantum well materials may also be used to produce switches and modulators. To understand these properties as well as the spectral gain characteristics of laser material, one would like to measure nonlinear absorption and the transition to gain as a function of excited carrier density and wavelength. The measurement of the absorption properties of very thin or transparent materials as a function of wavelength can be a very difficult problem, however. For a semiconductor SQW with peak absorbance, αL, of only 0.01, the transmission is 99%.

To measure changes in normal-incidence transmission one group used a pump–probe technique[1] on InAs/GaAs SQW's. Modulation on a monochromatic cw probe is caused by a chopped-cw pump beam and detected by means of a lock-in amplifier. Degenerate four-wave mixing has been demonstrated with multiple quantum wells[2] and could be used with SQW's, though less effectively. This requires tunable mode-locked lasers and produces very small signals because of the very thin grating thickness. Photoreflectance[3] provides a sensitive technique to measure field-induced changes in quantum wells but also results in data that are difficult to interpret.

The results presented here use a novel pump–probe technique to measure very small changes that occur in the absorption without the challenges of the above techniques. The scheme is based on the principle of differential detection. A balanced detection circuit has been designed and built that cancels the photocurrent to the first order. The probe beam is split into a sense beam and a reference beam, and a separate photodiode is used to measure each. The two photocurrents are subtracted and converted to a voltage by a transimpedance amplifier, all on one circuit board, shown in Fig. 1. The sense beam passes through the sample to be measured, whereas the reference beam is unaffected. With no change in sample transmission, the two photocurrents are nulled; a changing transmission produces a differential output voltage. This technique permits time-dependent measurement of small nonlinear transmission for nonlinear response times slower than the response time of the detection circuit.

Balancing the Detection

Critical to this method is the ability to null the photocurrents; nulling to 0.1% of the common signal voltage is necessary to see changes in transmission of approximately this magnitude. For Gaussian-shaped pulses the time delay must be controlled to within 3% of the pulse width to keep the amplitude difference less than 0.1%. This corresponds to controlling the path length to within 14 mm for a 3-ns pulse. A slight mismatch in the relative beam delay is acceptable because the signal appears as an odd time function with a null point in the center. The amplitude ratio of the probe beams must be controlled to

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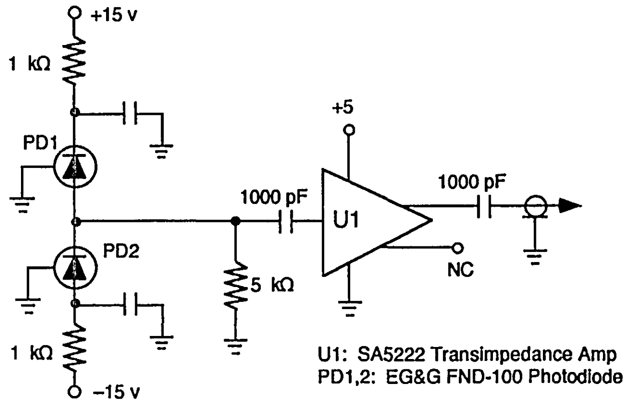

Fig. 1. Electronic schematic of a balanced detection circuit.

the same order as the desired precision of change in transmission. High-quality variable neutral-density (ND) filters are needed to achieve amplitude control of 0.1%; these filters also prevent lateral translation or time delay, which would be caused by insertion of successive glass filters. A 10-cm linear ND filter of optical density 0–1 requires position control to 0.1 mm.

The shape of the current pulse is the other factor that must be the same in the two photodiodes. The photodiodes need to be matched, and the incident light must hit only their active region; outside this region the rise time is much greater and will produce a long fall time, or tail on the pulse. The intensity also must not be so large as to saturate the detector depletion region, or such a tail will also occur.

To produce the largest voltage, the photodiode and transimpedance amplifier response times should be faster than the pulse width. The photodiodes used here have a 1-ns rise and fall time and a relatively large (5-mm^2) active region for ease in focusing the beams. The amplifier is a high-speed (160-MHz), high-transimpedance (8-kΩ) amplifier, Signetics SA5222. It is ac coupled to pass only signals above 1 MHz to limit the noise and improve stability. The resistor at the junction of the two photodiodes is used to pull this node to ground to make the two biases equal without varying the ±15-V supply. The components used are generally surface mounted on a carefully designed, double-sided epoxy board, as is customary with rf design. The capacitors on the photodiodes are used for low-pass filtering and have a value of 0.1 μF.

If the two optical beams and detectors are not exactly matched, the circuit will produce a constant offset voltage signal. This offset appears in both the signal (where change in transmission will be measured) and in the background, where no pump is applied (as described in the section Analysis of Differential Transmission). This offset may be eliminated by subtraction but must not be so large as to saturate the transimpedance amplifier or the detection electronics. The ratio of transmission change to offset must also be larger than the signal-to-noise ratio of the detection electronics. In our measurements a boxcar averager with a range of 200 mV and a resolution of 1 mV was used. The sum of the signal and offset also must lie within this range.

Analysis of Differential Transmission

To measure the change in transmission induced by pumping, the voltage output of the circuit is sampled and averaged with a boxcar averager (EG&G Model 4400) with and without the pump. The intensities that are needed to see nonlinearities in semiconductors may also produce large amounts of photoluminescence from the sample. To correct for this photoluminescence (PL) signal that is present with the pump, an additional measurement must also be made with the probe beams locked. The differential voltage caused by pumping is therefore

$$\Delta V = V(\text{pumped}) - V(\text{unpumped}) - \text{PL}. \qquad (1)$$

Transmission, T, through the sample is the ratio of output power, P_o, to input power, P_i. Differential transmission caused by a perturbation in the transmitted per, ΔP, is

$$\Delta T = \frac{P_o + \Delta P}{P_i} - \frac{P_o}{P_i} = \frac{\Delta P}{P_i}. \qquad (2)$$

The silicon photodiodes have a radiant sensitivity, S, in amps per watt, so

$$P_o = \frac{I_d}{S} = \frac{V_o}{SR_z}, \qquad (3)$$

where I_d is the photodiode current, R_z is the transimpedance (8 kΩ for our amplifier), and $V_o(=I_dR_z)$ is the output voltage measured at the transimpedance amp for one photodiode. A similar expression may be written relating ΔP and ΔV. From Eq. (2) and $T = P_o/P_i$,

$$\frac{\Delta T}{T} = \frac{\Delta P}{P_o} = \frac{\Delta V/SR_z}{I_d/S} = \frac{\Delta V}{I_dR_z}. \qquad (4)$$

By measuring the instantaneous power that is incident upon the detectors, P_o, at the boxcar sample time point, I_d may be calculated with Eq. (3). Combining Eqs. (1) and (4) therefore gives the percent change in transmission.

The above analysis assumes that the detectors, amplifier, and boxcar do not distort the pulse shape. If the impulse-response pulse width of the electronics, τ_e, is greater than the probe optical pulse width, τ_o, the ΔV pulse is effectively broadened and reduced in amplitude. To correct for this the measured ΔV can be multiplied by the time-constant factor to deconvolve the amplifier impulse response. Thus Eqs. (4) becomes

$$\frac{\Delta T}{T} = \frac{(\tau_o{}^2 + \tau_e{}^2)^{1/2}}{\tau_o} = \frac{\Delta V}{I_dR_z}. \qquad (5)$$

For pulse widths much shorter than τ_e, such as in mode-locked lasers, this technique becomes less valuable. Replacing the transimpedance amplifier with a 50-Ω load and using faster photodiodes would help when $\tau_o < 62$ ps.

The power absorption coefficient, α, is related to transmission by

$$\alpha = \frac{1}{L}\ln(T), \tag{6}$$

where L is the length of the absorbing medium. For the SQW absorption discussed here, the change in transmission is typically less than 1%. Differentiating Eq. (6) gives the change in absorption as

$$\Delta\alpha = -\frac{\Delta T}{TL}\cdot \tag{7}$$

In the research discussed here, this change in transmission arises from a material susceptibility that is nonlinear with the optical intensity. For a 100-Å SQW ($L = 10^{-6}$ cm), $\Delta\alpha$ can be large even for small changes in T.

Noise Limitations

The boxcar was used to reduce the predominant, limiting noise source: noise caused by random sources. The fundamental limitation to detecting small differential photocurrents on large signals is the shot noise of the detector. The shot noise, given by

$$I_n = (2qI_d\Delta f)^{1/2}, \tag{8}$$

shows that the signal to noise, I_d/I_n, increases with the square root of the photocurrent, I_d (q is the electron charge and Δf is the bandwidth, which was 160 MHz in the experiment reported here). The photodiode should be operating in the linear regime, so the maximum current should be limited to approximately 5 mA for the diodes used here. At 1 mA, the noise current from Eq. (8) is 50 nA; from this fact the shot-noise limit to measurable $\Delta T/T$ is approximately 5×10^{-5}. The transimpedance amplifier input noise of 55 nA is the same magnitude as the photodiode noise.

Vibration or lateral drift in the ND filter previously discussed or in the sample also may cause fluctuation in the measurement because of positional dependence of transmission (caused by spatial nonuniformities in the sample's case). Roughness in the sample (from sources such as a bad etch) also causes light to scatter from the signal beam and to not reach the sense beam photodiode. This difference from the reference beam can cause large amounts of noise in ΔV.

We believe the primary source of noise in our experiment arises from sensitivity variations in the photodiodes across their active regions. The spatial energy distribution of the probe dye laser fluctuates considerably with each shot. The ND filter is able to balance the total average fluence of each beam, but

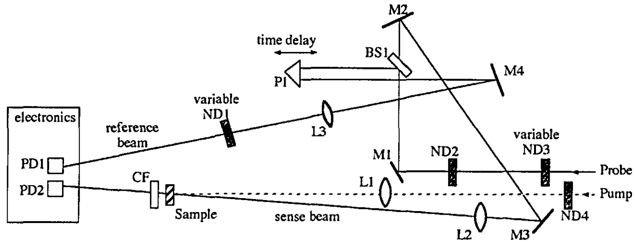

Fig. 2. Experimental setup for measurement of nonlinear pump–probe transmission.

the sensitivity of the photodiodes may vary spatially by as much as 10% on a 25-μm scale. Thus spatial variations in the probe cause fluctuations in the sensitivity and would be different in the two diodes. Spatial filtering of the probe beam before splitting it into reference and sense beams could reduce this noise source.

The experiment reported here had shot-to-shot variation in ΔV of ±20 mV at a diode current of 1.5 mA; the use of boxcar averaging over many shots improved this variation to approximately ±2 mV. From Eq. (5) this produces a limitation on measuring $\Delta T/T$ of approximately 5×10^{-4}. This result is almost an order of magnitude larger than the rms noise sum of the diode shot noise and the transimpedance amplifier input noise. Increasing the diode current does not improve this experimental limit, because the variance in ΔV increases with current. The primary limit to measuring $\Delta T/T$ is drift in the sampled voltage signal, which prevents longer boxcar averaging; we used a 128-point average with a measurement time of 13 s. We believe this drift is caused by long-term change in the spatial profile of the probe dye laser.

Optical Setup

We demonstrated this concept by measuring the pump-induced change in transmission of a probe signal through a SQW of (Cd, Zn)Se in ZnSe grown by molecular beam epitaxy. A schematic of the optical configuration is shown in Fig. 2. The pump and probe are from two dye lasers with 3-ns pulse widths, pumped by the third-harmonic of a Q-switched Nd:YAG laser. The probe wavelength varies from 470 to 520 nm. The pump wavelength of 435 nm is chosen short enough to be separated from the probe with a color filter, CF, and to be strongly absorbed in the quantum well barrier region. The pump's intensity is varied by ND filter ND4. Lens L1 focuses the pump to a spot diameter of 400 μm on the sample. Mirrors M1–M3 are used to delay the probe to overlap in time with the pump pulse. The probe is split into the sense and reference beams by beam splitter BS1. Prism P1 is mounted on a translation stage so the delay between the two probe beams may be accurately controlled without requiring realignment. Lens L2 focuses the sense beam to a 200-μm diameter. The larger pump spot allows the two spots to be aligned visually, ensuring that the sense beam covers an area that is completely pumped. The focal length of L2, is 500 mm, so a detector-to-sample distance of 30 cm does not require an additional lens. Also, this weak focusing causes less variation in spot size with sample translation, eases alignment of the many beams and components, and eliminates the photoluminescence signal at the detectors for all but the highest intensities. The two photodiodes, PD1 and PD2, are mounted 8 cm apart on the same circuit board as the transimpedance amplifier. ND1 is a linear variable-reflectance ND filter of 0–1.0 density that is used to vary the amplitude of the reference beam to null the difference signal. ND2 is a series of filters used to attenuate the probe greatly. ND3 is a circular variable-reflectance ND filter of 0–2.0 density that is used to fix the intensity of the incident signal beam at a constant value. This causes I_d to be the same for each measurement.

Conclusion

This limit of better than 10^{-3} in measuring $\Delta T/T$ is sufficient to observe the nonlinearities in the SQW structures. Figure 3 shows the result for a 75-Å SQW of (Zn, Cd)Se in ZnSe, which is described in greater detail elsewhere.[4] The peak at 512 nm is the $n = 1$ excitonic absorption resonance that is nonlinear with an incident optical field. In this material, the response time was much less than the laser pulse width and the time response of the electronics, so time-resolved measurements were not possible.

In conclusion we have demonstrated a novel technique to measure changes in transmission of better than 0.1%, with time resolution of better than 10 ns.

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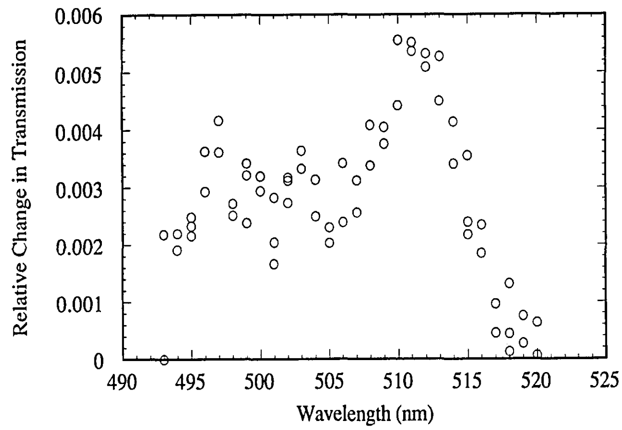

Fig. 3. Fractional change in transmission ($\Delta T/T$) of a probe signal versus wavelength through a $Cd_xZn_{1-x}Se/ZnSe$ ($x = 0.26$) 75-Å single quantum well in the presence of a pump intensity of 10 kW/cm^2 in.

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