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# Wide band AC balanced homodyne detection of weak coherent pulses

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**Abstract**

A wide band AC balanced homodyne detection technique was applied to measure the amplitude of coherent pulses. The ultimate sensitivity given by a peak signal to noise ratio (S/N) = 1 of our system is estimated to be about 0.25 fW ($3.3 \times 10^{-24}$ J/pulse or a photon number of $1.25 \times 10^{-5}$ photons/pulse). As a demonstration for probing very weak ultrafast coherent optical processes, an exciton-polariton oscillation in a GaAs single quantum well microcavity was observed up to nine oscillation periods. © 1998 Elsevier Science B.V.

*Keywords:* High sensitivity; Femtosecond pulses; AC balanced homodyne detection; Exciton-polariton oscillation in microcavity

Recent progress in femtosecond laser pulse generation and detection techniques allows us to explore ultrafast optical processes in various materials. In these experiments, a very weak optical signal from a sample has to be detected maintaining a short temporal resolution. Conventional time-resolved photon detection techniques such as those using a streak camera and a nonlinear up-conversion correlator do not provide femtosecond temporal resolution and single photon counting sensitivity, simultaneously. New techniques such as DC balanced homodyne detection (DC-BHD) [1,2], spectral interferometry [3,4], and two-photon interferometry [5] have been demonstrated to measure ultrafast coherent optical processes with temporal resolutions better than 10 fs, excluding pump pulse duration, and sensitivity as high as $4.2 \times 10^{-20}$ J/pulse.

To achieve much higher sensitivity with high temporal resolution for wide band optical processes, we have constructed an AC balanced homodyne detection (AC-BHD) system with a sensitivity of sub-femto watts and wide wavelength band depending only on each of the detectors and non-polarized beam splitter. Using this system, detection of coherent optical pulses operating at 76 MHz with an average power of 10 fW, which corresponds to an average pulse energy of $1.3 \times 10^{-22}$ J/pulse or average photon number of $5 \times 10^{-4}$ photons/pulse, was demonstrated with a S/N(signal to noise ratio) = 8 dB. As one application for probing very weak ultrafast coherent optical processes, exciton-polariton oscillation in a GaAs single quantum well microcavity was observed up to nine oscillation periods in a weak excitation linear regime.

A setup of the AC-BHD system to investigate coherent optical process of a GaAs signal quantum well microcavity sample installed in a He cryostat is shown in Fig. 1. Optical pulses from a Ti:sapphire laser (Coherent Mira Model 900) operating at 76 MHz are split with a non-

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polarized beam splitter (BS1, S32, Suruga, wavelength band from 500 nm to 1.1 μm) into two arms of a modified Mach-Zehnder interferometer. One beam is used as a local oscillator wave while the other is used as a probe wave. The probe pulses are delayed by a time $\tau$ with a corner mirror (CM1) placed on a translational stage and are recombined with the local oscillator pulses at a second beam splitter (BS2, S32, Suruga). The interferometer outputs are detected by two identical photodetectors (PD1 and PD2) and the photocurrents from PD1 and PD2 are fed into a differential amplifier (CA-251F4, NF Corp.), through a handmade filter circuit to cut off the repetition frequency of laser pulses. The intensity noise of the local oscillator pulses was suppressed by more than 35 dB due to the common mode rejection of the balanced homodyne detection system. To eliminate the instability of the interferometer, the optical path length of the probe pulses is modulated by $\Delta l$ at a frequency $\nu_l$ by a mirror M4 mounted on a PZT scanner. This optical path length modulation generates a sinusoidal signal in the differential amplifier output with a frequency $\nu_l(\Delta l/\lambda) = \nu_m$, where $\lambda$ is the center wavelength of the optical pulses. The time-dependent amplitude of the coherent probe pulses can be detected by measuring the amplitude of the sinusoidal output signal at the frequency $\nu_m$ through two stages of voltage tunable bandpass filters (VT-2BPA, NF Corp., band width of 250 Hz) and an AC voltage meter as a function of the time delay $\tau$.

Because the amplitude of the sinusoidal output signal due to the optical path difference modulation is insensitive to the long- and short-term instabilities of the Mach-Zehnder interferometer and the electronic circuits noise is suppressed by AC detection with very narrow frequency band of 250 Hz, while collecting data over a long time period, AC-BHD method has better sensitivity than the DC-BHD method.

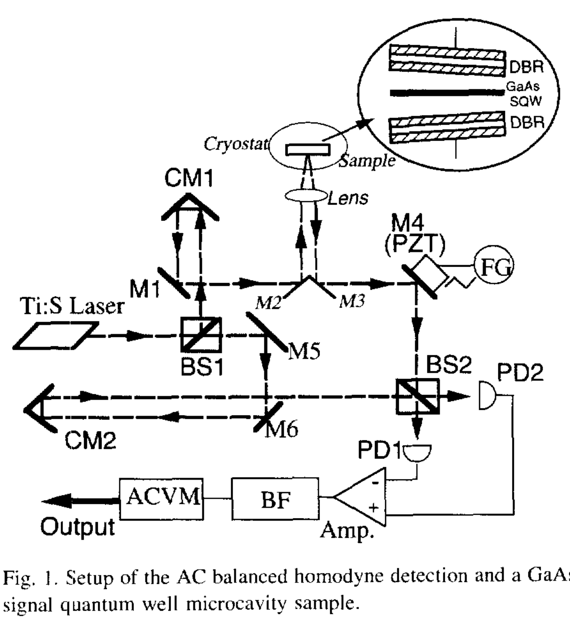


Fig. 1. Setup of the AC balanced homodyne detection and a GaAs signal quantum well microcavity sample.

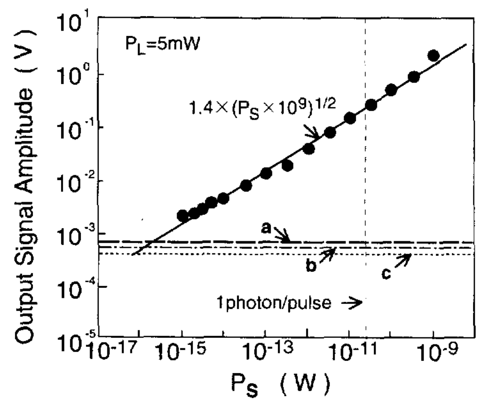


Fig. 2. AC balanced homodyne detected signal versus the average power of probe pulses. Dotted lines 'a', 'b', and 'c' are the measured noise of the local oscillator pulses with $P_L = 5$ mW, $P_L = 0$, and the theoretical shot-noise limit of the system, respectively.

On the other hand, instead of the combination of the wavelength-dependent optical components such as a waveplate and polarizer used in the DC-BHD method [2], we realized the balance by adjusting the coupling efficiency of two photodetectors. Therefore, wide band from at least 500 nm to 1 μm due to the bands of the beam splitters and photodetectors is really easy to be alighted for any optical processes to be observed.

To find out an ultimate sensitivity of this AC-BHD system, the balanced homodyne outputs were measured as a function of average power of probe pulses where the local oscillator pulse powers were kept constant at $P_L = 5$ mW. Mirrors M2 and M3 in Fig. 1 were removed so that the attenuated Ti:sapphire laser output pulses were directly detected without interacting with the sample. The Ti:sapphire laser was operated at 800 nm with a repetition rate of 76 MHz. The measured pulse profile is shown in Fig. 2. The modulated path length difference was set to be about 800 nm and the modulation frequency was optimized and was set to 150 Hz. The horizontal dotted lines 'a' and 'b' are the measured noise of the local oscillator pulses at $P_L = 5$ mW and $P_L = 5$ mW and $P_L = 0$ (the thermal dark noise of the detection system), respectively. The trace 'c' is the theoretical shot-noise limit of the photodetectors with quantum efficiencies of 0.8 at a detection bandwidth of 250 Hz, which optimizes the detection S/N ratio for this case [6]. As shown in the figure, the balanced homodyne outputs decrease proportionally to $\sqrt{P_S}$ (solid line) as expected [7] where $P_S$ is the average power of the probe pulses. From the crossing point between the solid line and the dotted line 'a', the ultimate sensitivity defined by S/N = 1 is estimated to be 0.25 fW, which corresponds to an average pulse energy of $3.3 \times 10^{-24}$ J/pulse or a photon number of $1.25 \times 10^{-5}$ photons/pulse.

The dotted line ‘a’ is slightly higher than the sum of ‘b’ and ‘c’. The reason why this occurs can be attributed to the residual laser intensity noise. In fact, the common mode suppression of 35 dB by the AC-BHD is still not enough to eliminate the laser intensity noise completely. Therefore, a higher sensitivity can be expected by using a laser source with lower intensity noise and/or by using a lock-in detection to decrease further the bandwidth of the detection circuit. It has been confirmed experimentally that the S/N was indeed improved by 10 dB by using a lock-in detection technique [8].

Fig. 3 shows the AC-BHD output of the transform limit pulses from the Ti:sapphire laser. The modulated path length difference and the modulation frequency were the same as those mentioned above. The probe pulses power was attenuated to $P_S = 10$ fW and the local oscillator power was $P_L = 5$ mW. Sampling time of each data point of 10 ms due to the number of averaged photons per sampling points is about 380. The horizontal axis is the delay length introduced by the displacement of the CM2 and the vertical axis is the detected AC-BHD output signal plotted in logarithmic scale. The full width at half maximum of the profile is about 146 μm. Considering a $\mathrm{sech}^2$ intensity profile of the Ti:sapphire laser, the duration of the pulses in transform limit was evaluated to be about 225 fs which agrees well with the pulse width measured with a SHG autocorrelator placed parallel to the AC-BHD system. From Fig. 3, a S/N of 8 dB was achieved at $P_S = 10$ fW, which agrees with the results shown in Fig. 2.

Since the temporal resolution $\Delta t_s$ of the detection system can be estimated as $\Delta t_s = [(\Delta t_l)^2 + (\Delta t_m)^2]^{1/2}$ by assuming Gaussian spread functions, where $\Delta t_l$ and $\Delta t_m$ are the temporal resolution due to the laser pulse duration and the optical path difference modulation, respectively, we have investigated the relationship between the modulated optical path difference and the S/N of the AC-BHD output. It was found that the S/N is constant as the modulated optical path difference exceeds one optical wavelength. The modulated optical path difference of one wavelength corresponds to 3 fs temporal resolution when the wavelength is about 800 nm.

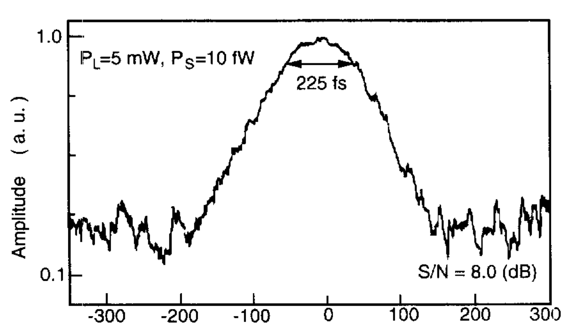


Fig. 3. The observed pulse from the Ti:sapphire laser operating at 800 nm in logarithmic scale. $P_L$ and $P_S$ were 5 mW and 10 fW, respectively.

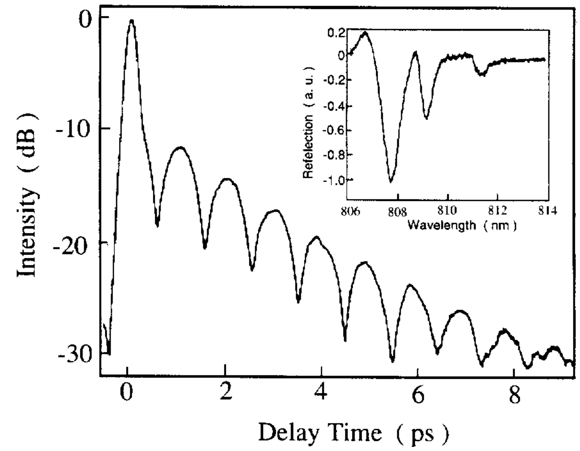


Fig. 4. Observed exciton-polariton oscillation in a GaAs single quantum well microcavity. The inset is the measured reflective spectral linewidth at the same position of the sample.

To demonstrate the ultra-sensitive detection capability of our AC-BHD system, we have measured the coherent exciton-polariton oscillation in a GaAs single quantum well semiconductor microcavity [2,9,10]. Optical pulses with a duration of 150 fs were used to excite the GaAs single quantum well in a microcavity. The probe pulses were incident onto the microcavity sample with an incident angle smaller than 2.5° and the reflected pulses from the sample were combined with the local oscillator pulses at BS2 as shown in Fig. 1. The microcavity is a half-wavelength cavity sandwiched between two DBR mirrors consisting of 15.5 and 30 pairs of alternate quarter-wavelength AlGaAs/AlAs layers [7], respectively. A 20 nm GaAs quantum well is placed at the center of the half-wavelength cavity layer. Fig. 4 shows the measured amplitude of the reflected pulses under a weak pumping power of approximately 0.5 μW on the spot size of about 30 μm. The peak at $\tau = 0$ corresponds to the direct reflection of the laser pulses from the sample surface and was used as a zero time marker. The subsequent nine peaks correspond to the exciton-polariton oscillation. The oscillation period of 1.1 ps is consistent with the light hole exciton polariton splitting of 3 meV. The decay time of the exciton-polariton oscillation is evaluated to be 1.3 ps from the exponential decay rate of the nine peaks, which is in close agreement with the corresponding 0.9 nm spectral linewidth as shown in the inset of Fig. 4.

In conclusion, we have demonstrated an ultra sensitive wide band AC-BHD technique useful for probing very weak ultrafast coherent optical processes. The ultimate sensitivity, which is defined by S/N = 1, is estimated to be about 0.25 fW which corresponds to an average pulse energy of $3.3 \times 10^{-24}$ J/pulse or an average photon number of $1.25 \times 10^{-5}$ photons/pulse. The temporal resolution determined by the optical path difference modulation is about one center wavelength of the pulses. With this AC-BHD system, we have demonstrated a detection of coherent optical pulses with an average power of 10 fW ($1.3 \times 10^{-22}$ J/pulse or $5 \times 10^{-4}$ photons/pulse), with S/N = 8 dB. As one application for probing very weak ultrafast coherent optical processes, exciton-polariton oscillation in a GaAs single quantum well microcavity was observed up to nine oscillation periods.

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