

# Quantum interference in semiconductors controlled by carrier-envelope phase

P. A. Roos, T. M. Fortier, D. J. Jones, and S. T. Cundiff

JILA, NIST, University of Colorado, UCB 440, Boulder, CO 80309-0440, USA  
Phone: (303) 492-8515, Email: roos@jila.colorado.edu

R. D. R. Bhat and J. E. Sipe

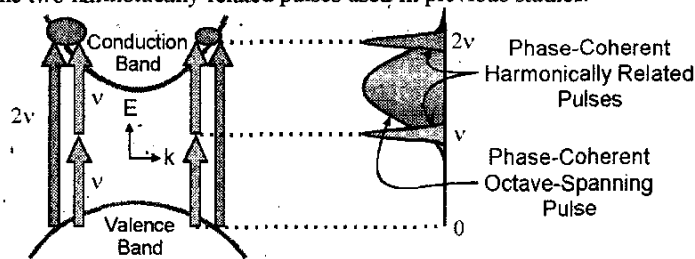
Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada  
Phone: (416) 978-4517, Email: rbhat@physics.utoronto.ca

**Abstract:** We demonstrate that the carrier-envelope phase of ultrashort pulses can be used to control injected photocurrents via quantum interference in low-temperature-grown gallium arsenide.

**OCIS codes:** (320.7130) Ultrafast processes in condensed matter, including semiconductors; (120.5050) Phase measurement; (190.5970) Semiconductor nonlinear optics including MQW; (270.1670) Coherent optical effects;

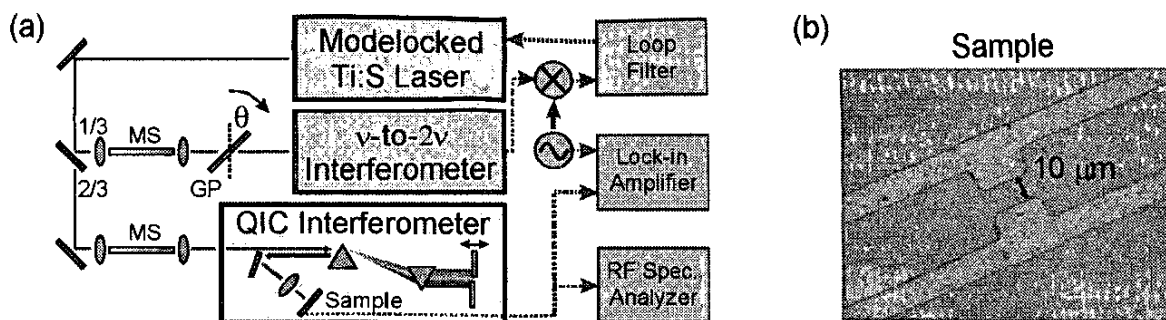
The observation of quantum interference control (QIC) of injected photocurrents in semiconductors was first reported in 1997 [1], and has since been extensively studied both experimentally and theoretically [2]. When two phase-coherent, harmonically related pulses are focused onto a metal-semiconductor-metal (MSM) structure, the direction and magnitude of the optically injected photocurrents can be controlled by adjusting the relative phase of the two incident pulses. This effect is due to quantum interference between single- and two-photon absorption in the semiconductor as depicted in Fig. 1 (see caption for description).

In this work, we demonstrate QIC using *single* ultrashort laser pulses rather than pairs of harmonically related pulses. In this case, the resulting photocurrent is sensitive to the actual phase of the optical carrier relative to the pulse envelope (the carrier-envelope phase) rather than the phase difference between two separate pulses. The ability to generate the phase-stable pulses that are required to observe this effect is enabled by recent efforts to stabilize the carrier-envelope phase of mode-locked femtosecond lasers. Many researchers currently use an elegant self-referencing technique known as  $\nu$ -to- $2\nu$  stabilization for this purpose [3]. This involves interferometrically comparing the optical phase of the low frequency tail of an octave-spanning (spanning a factor of two) pulse spectrum at  $\nu$  with that of the high frequency tail at  $2\nu$  through second harmonic generation. The resulting beat note is detected and used as an error signal in a feedback loop to stabilize the carrier-envelope phase in the time domain [4]. Once this phase is stabilized for an octave-spanning pulse, sufficient coherence can be achieved between the comb components at frequencies  $\nu$  and  $2\nu$ . Fig. 1 shows that these low and high frequency tails of the broad pulse spectrum can replace the two harmonically related pulses used in previous studies.



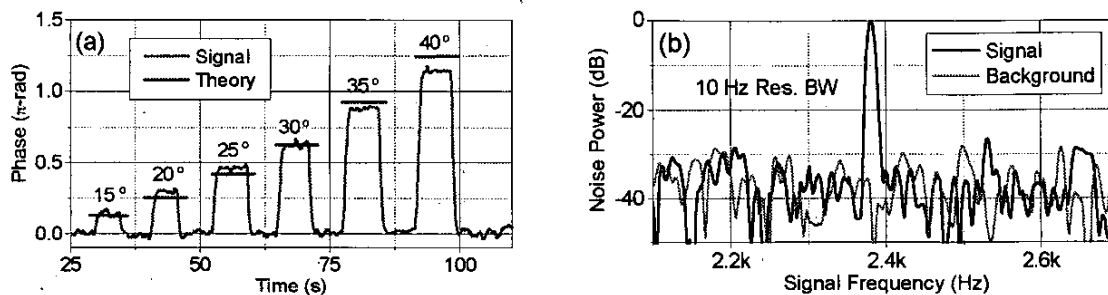
**Fig. 1:** Quantum interference between single- and two-photon absorption in a direct-gap semiconductor. For the case where the two quantum pathways interfere constructively in the  $-k$  direction and destructively for  $+k$ , an imbalance in the carrier population (represented by dark ovals) occurs, resulting in a net photocurrent in the positive direction. We use the carrier-envelope-phase of single octave-spanning pulses to control the quantum interference rather than pairs of harmonically related pulses.

As shown in Fig. 2(a), we broaden one-third of the light from a modelocked Ti:S laser in a microstructure fiber, pass it through a thin glass plate, and use it in a feedback loop to stabilize the evolution of the laser's carrier-envelope phase to 2.38 kHz using the standard  $\nu$ -to- $2\nu$  technique [3]. We broaden the remaining light in a microstructure fiber, retroreflect it through a pair of prisms for time delay compensation, and focus it onto a low-temperature-grown gallium arsenide (LT-GaAs) sample with lithographic MSM structures [see Fig. 2(b) and Ref. [5] for details]. Because we stabilize the evolution of the carrier-envelope phase using the  $\nu$ -to- $2\nu$  interferometer, we can perform sensitive lock-in detection of the resulting signal from the sample at this frequency.



**Fig. 2:** (a) Experimental setup used to observe quantum interference control (QIC) with a single pulse train. Ti:S characteristics: pulse duration  $<20$  fs; average power  $<400$  mW (can be attenuated); repetition rate = 93 MHz. The average powers, spot diameters, and 10 dB spectral widths are 12.5 mW (1.22 mW),  $11.5 \pm 0.7 \mu\text{m}$  ( $10.2 \pm 0.7 \mu\text{m}$ ), and 90 nm (50 nm) for  $v$  and  $2v$ , respectively, at the sample. MS = microstructure. (b) LT-GaAs sample with lithographic metal-semiconductor-metal structure. The MSM gap is  $10 \mu\text{m}$ .

To confirm the QIC signal dependence on the carrier-envelope phase, we rotate the glass plate shown in Fig. 2(a). This shifts the carrier-envelope phase to which the Ti:S laser is locked. Figure 3(a) shows the detected signal phase from the lock-in amplifier as the glass plate is turned through six different angles. The dark bars indicate the predicted phase shifts based on the glass thickness and dispersion.



**Fig. 3:** (a) QIC signal phase measured using the lock-in amplifier while the thin glass plate is rotated through six different angles. Due to slow, small uncontrolled phase drifts, the plate is returned to its original position after each rotation for differential measurements. The dark bars indicate the theoretically predicted phase values. (b) QIC signal amplitude measured on a rf spectrum analyzer. The peak corresponds to a 1 mV signal.

Figure 3(b) shows the QIC signal amplitude as measured on a rf spectrum analyzer. We measure a maximum signal slightly greater than 1 mV, which corresponds to a signal-to-noise ratio of nearly 40 dB (10 Hz RBW). With improved signal fidelity, we anticipate that the QIC signal can be used as a solid-state means of stabilizing (rather than just measuring) the carrier-envelope phase evolution of octave-spanning pulse trains. This technique can be compared with other promising methods of solid-state carrier-envelope detection/stabilization [6,7].

- [1] A. Haché, Y. Kostoulas, R. Atanasov, J. L. P. Hughes, J. E. Sipe, and H. M. van Driel, "Observation of coherently controlled photocurrent in unbiased, bulk GaAs," *Phys. Rev. Lett.*, **78**, 306-309 (1997).
- [2] H. M. van Driel and J. E. Sipe, in *Ultrafast Phenomena in Semiconductors*, (Ed. K. -T. Tsen, Springer-Verlag, New York 2001) pp. 261-307, and references therein.
- [3] D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis," *Science* **288**, 635-639 (2000), and references therein.
- [4] S. T. Cundiff, "Phase stabilization of ultrashort optical pulses," *J. Phys. D* **35**, R43-R59 (2002).
- [5] P. A. Roos, Q. Quraishi, S. T. Cundiff, R. D. R. Bhat, and J. E. Sipe, "Characterization of quantum interference control of injected currents in LT-GaAs for carrier-envelope phase measurements," *Opt. Express* **11**, 2081-2090 (2003).
- [6] O. D. Mücke, T. Tritschler, M. Wegener, and U. Morgner, "Determining the carrier-envelope offset frequency of 5-fs pulses with extreme nonlinear optics in ZnO," *Opt. Lett.* **27**, 2127-2129 (2002).
- [7] C. Lemell, X.-M. Tong, F. Krausz, and J. Burgdörfer, "Electron emission from metal surfaces by ultrashort pulses: Determination of the carrier-envelope phase," *Phys. Rev. Lett.* **90**, 076403 (2003).