

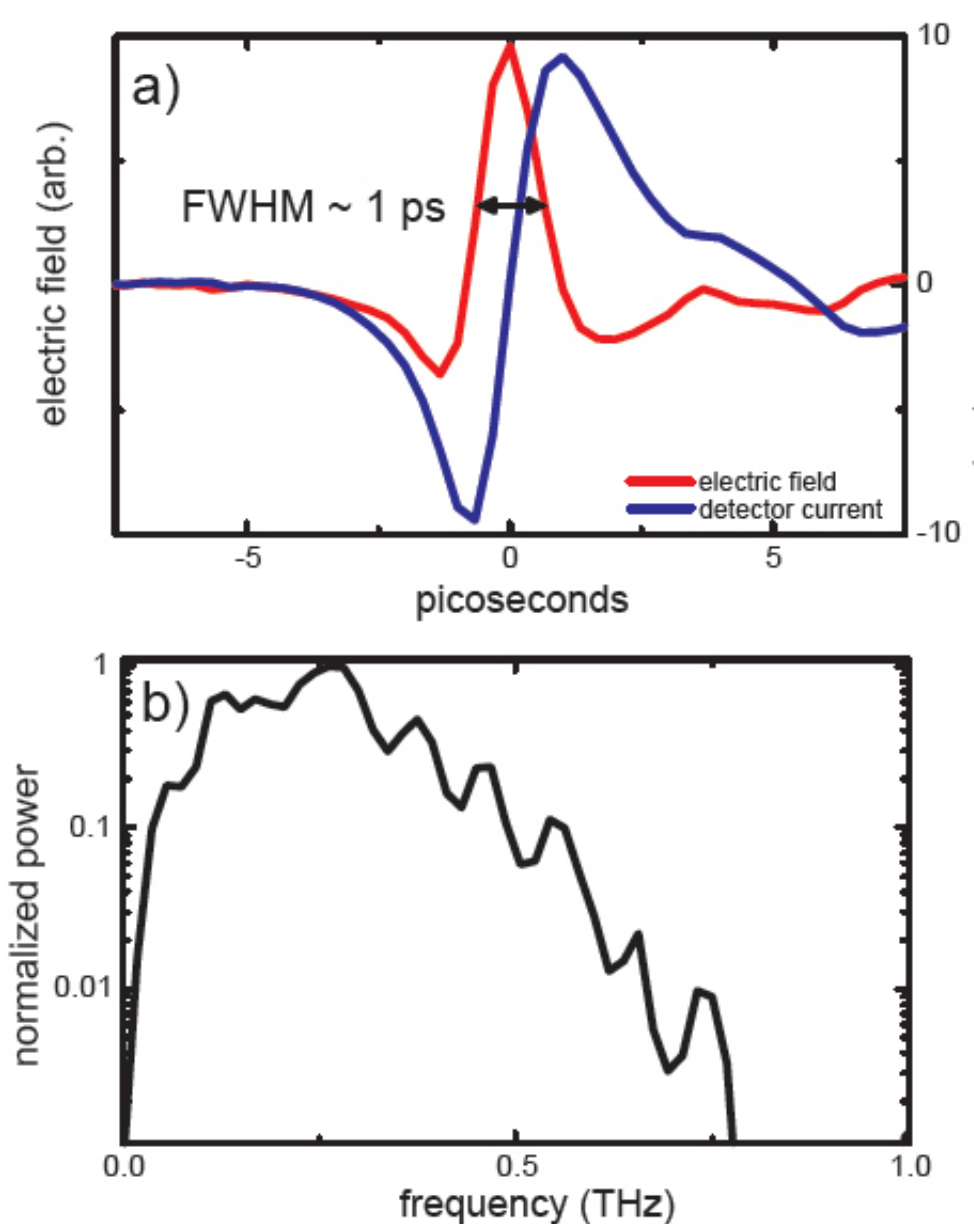
# DE-EXCITING RYDBERG ATOMS USING HALF-CYCLE THz PULSE TRAIN

PANKAJ K. MANDAL, KOUROSH AFROUSHEH, AND ANDREW SPECK

ROWLAND INSTITUTE AT HARVARD, HARVARD UNIVERSITY

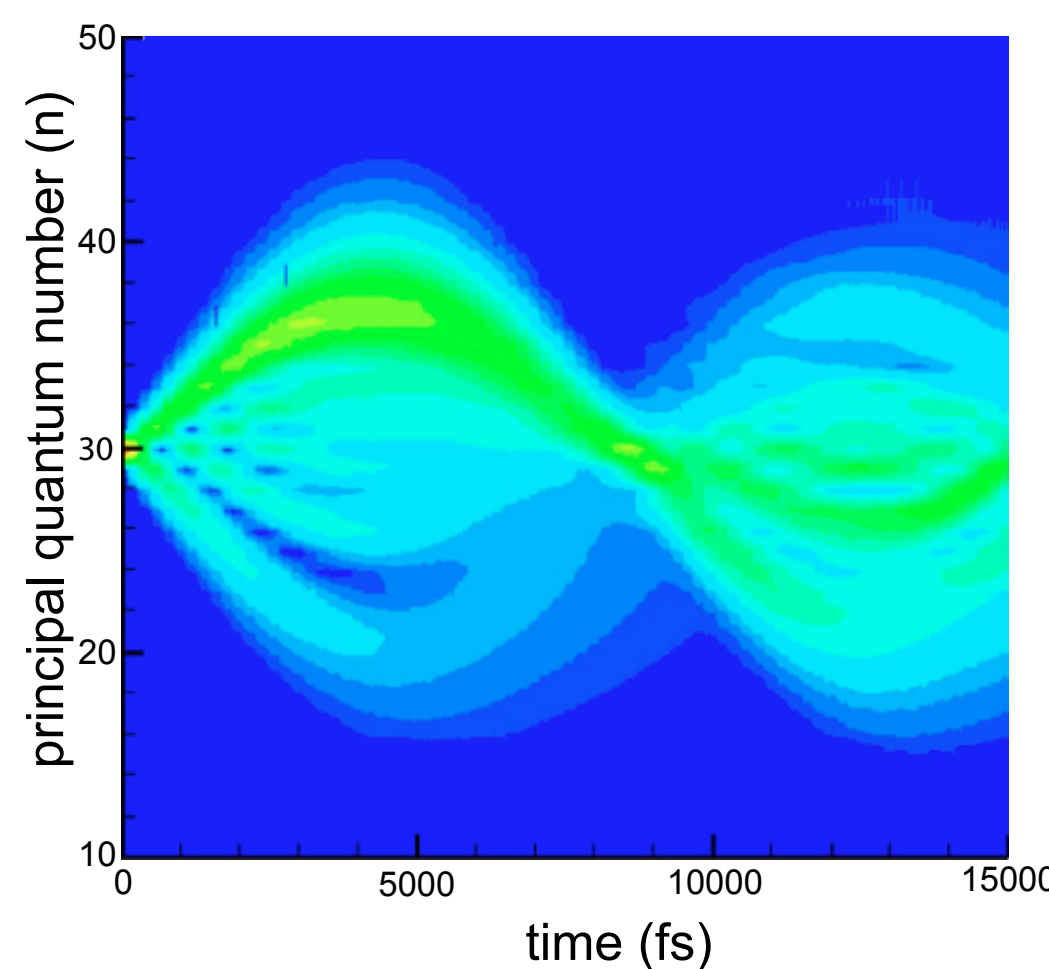
## INTERACTIONS OF RYDBERG ATOMS WITH TERAHERTZ RADIATION

Ultra-cold Rydberg atoms provide a fascinating regime in which to explore atomic states that exhibit both classical and quantum properties. The objective of our research is to study the interaction of these systems with unipolar terahertz electromagnetic pulses (half cycle pulses). In particular, these pulses provide an impulsive kick to the excited electron and thus interact in a much different manner than traditional bipolar continuous wave laser radiation. In principle this broadband technique should allow the efficient de-excitation of antihydrogen atoms from the currently produced mix of excited states<sup>1</sup> to a lower  $n$  state which will decay more efficiently to the ground state ( $\tau \propto n^5/\log n$ ) which is a necessary prerequisite for a CPT comparison with hydrogen.

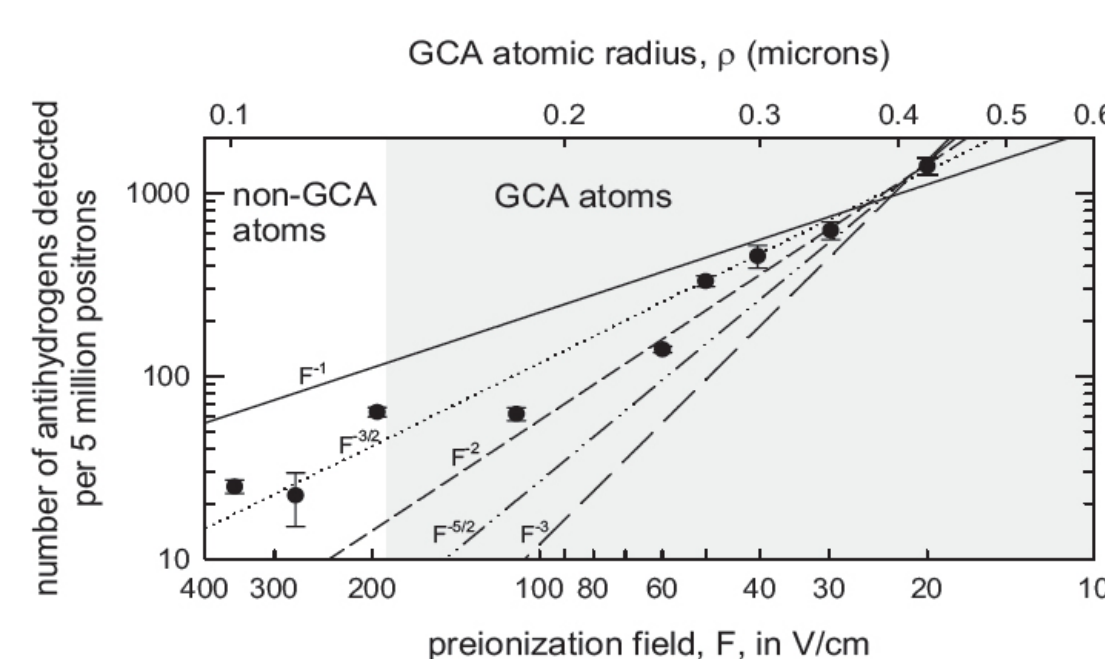


A typical half cycle's pulse (a) temporal waveform and (b) frequency spectrum.

- HCP's are primarily unipolar and have a pulse width of approximately 1 ps and amplitudes of 1 kV/cm.
- As a Rydberg atom's orbit period scales as  $n^3$ , for many energy levels the effect of an HCP can be treated as a sudden impulse on the electron.
- For example,  $\tau \sim 10$  ps for  $n \sim 40$ .
- Theoretical studies suggest that the application of a number of these half-cycle pulses should drive the Rydberg atoms to different  $n$  quantum states<sup>2</sup>.
- In a 1-D model system a chirped pulse train with varying repetition rate the direction of population transfer can be controlled by the timing of the chirp<sup>3</sup>.
- Experimental studies have demonstrated this technique for atoms in very high Rydberg states ( $n \sim 350$  to  $700$ )<sup>4</sup>.
- However no studies have been performed in the relevant range of Rydberg states for antihydrogen studies.



Result of a simulation showing the redistribution of the Rydberg state population due to interactions with half cycle pulses (From Ref. 2).



Currently antihydrogen atoms are produced in a broad range of Rydberg states (From Ref. 1).

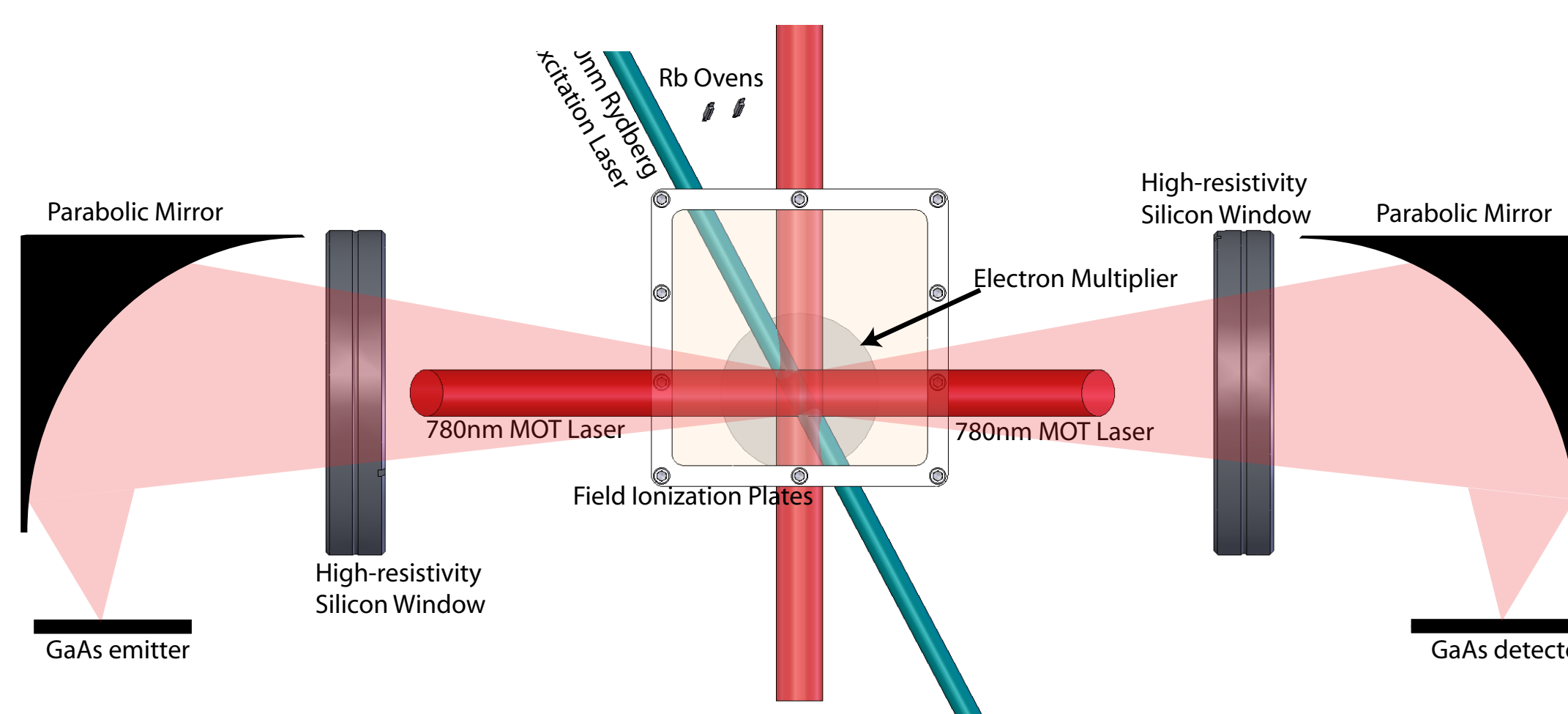
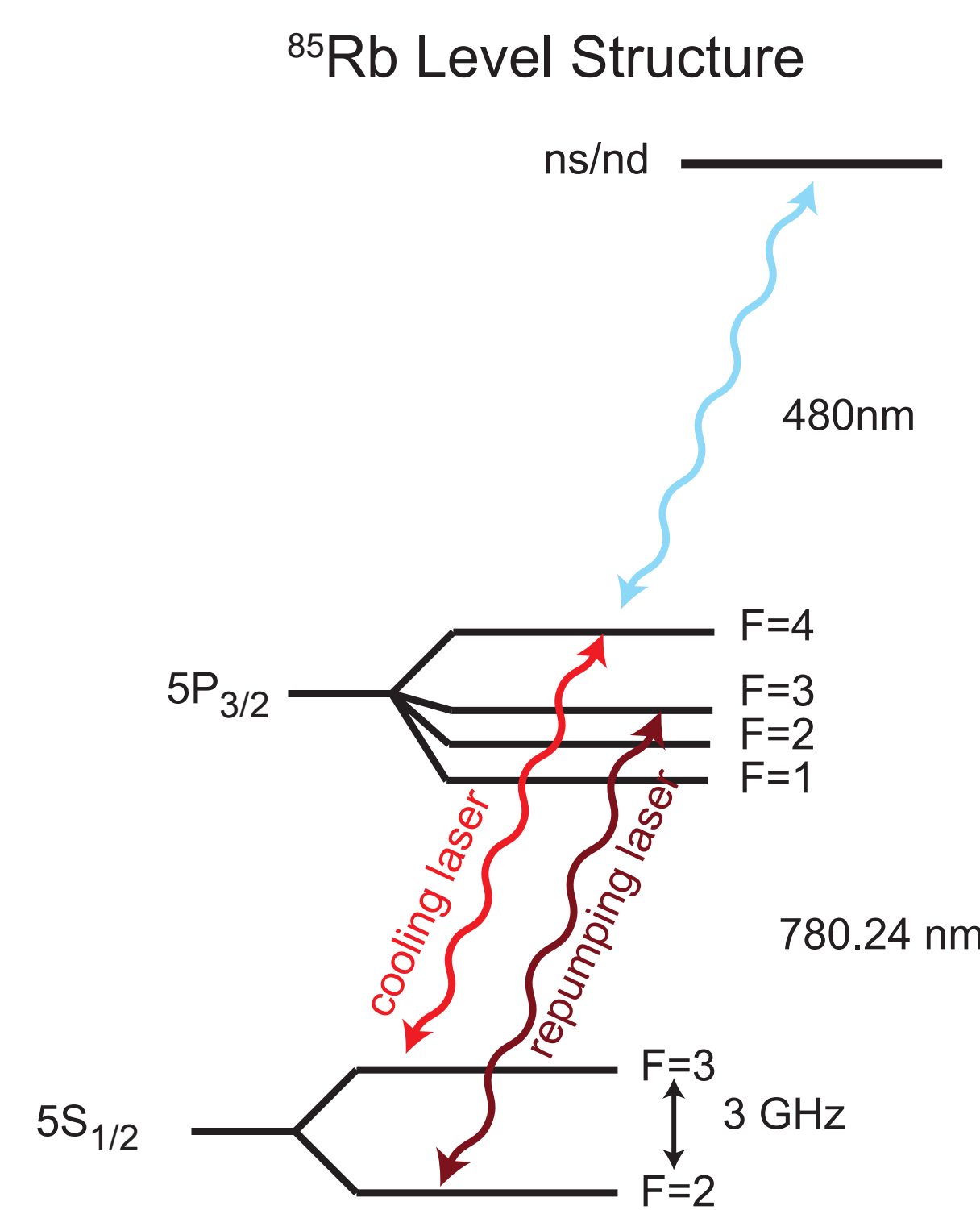
Hollow-core Photonic Band-gap crystal fiber is used to deliver the laser pulses to the photo-conductive antenna.

## EXPERIMENTAL PLANS

- <sup>85</sup>Rb atoms trapped in a magneto-optical trap (MOT) are first excited to  $5P_{3/2}$  and then to a Rydberg state ( $n \sim 40$ ) which is predominantly of  $d$  character for a broadband excitation laser source.
- Collisions between Rb atoms then change the  $d$  character to a mixture of  $\ell$  levels.
- A train of half-cycle pulses are then sent through the trapped atoms and the atomic state is allowed to evolve.
- The resulting state distribution is measured by applying an electric field pulse to ionize the atoms.

## RYDBERG ATOMS

- <sup>85</sup>Rb atoms are loaded from dispensers into a vapor cell MOT. This trap both confines the atoms in an approximately 2 mm dense cloud and cools the atoms to below 100  $\mu$ K which allows for a much increased interaction time.
- The trapping lasers provide the excitation to the  $5P_{3/2}$  level.
- A 480 nm pulsed OPO (with 3 mJ, 20 Hz pulses) excited the atoms to  $n \sim 40$ .
- Field ionization plates ionize the Rydberg atoms with the resulting electrons collected in an electron multiplier.



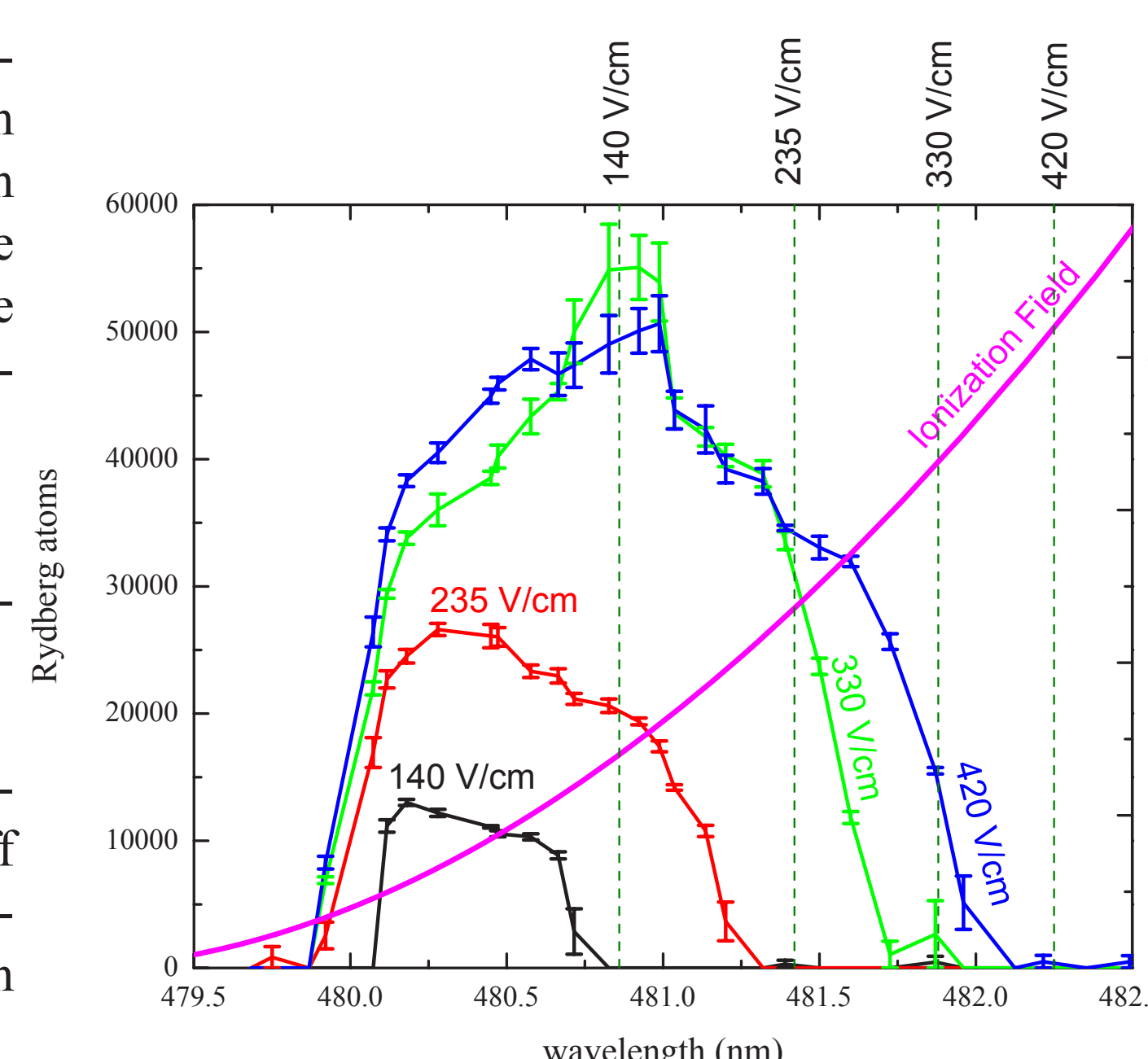
Our interaction chamber contains a MOT, field ionization plates and electron multiplier for detection, and silicon windows which allow for the entry of half cycle pulses.

Rydberg atoms field ionized for a given wavelength and electric field strength (black, red, green, and blue curves). The purple curve shows the classically expected ionization field:

$$F \approx \frac{3 \times 10^8}{n^4} \text{ V/cm}$$

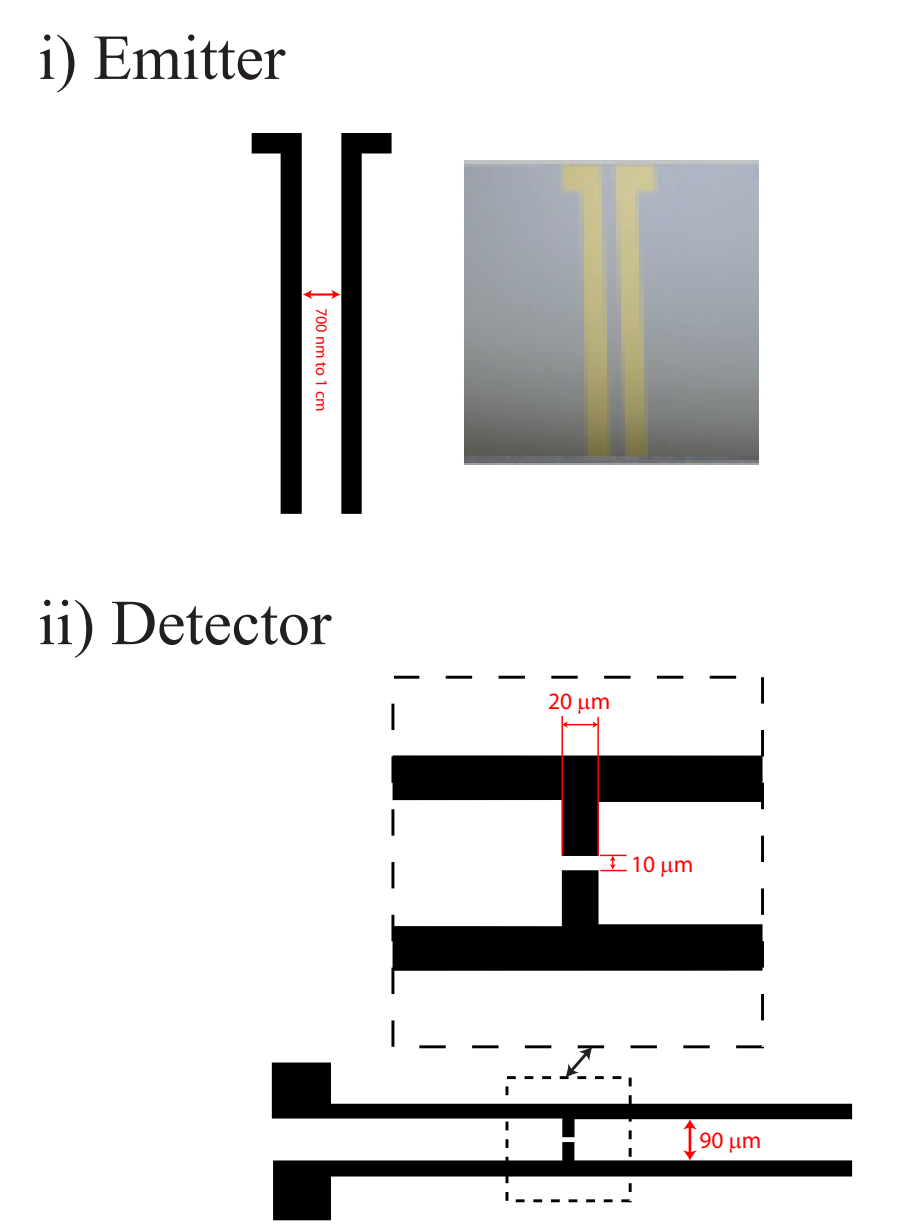
for states with a given transition wavelength.

Note the reasonable agreement with the upper cutoff which is set by the strongest bound states that can be ionized at a given field.

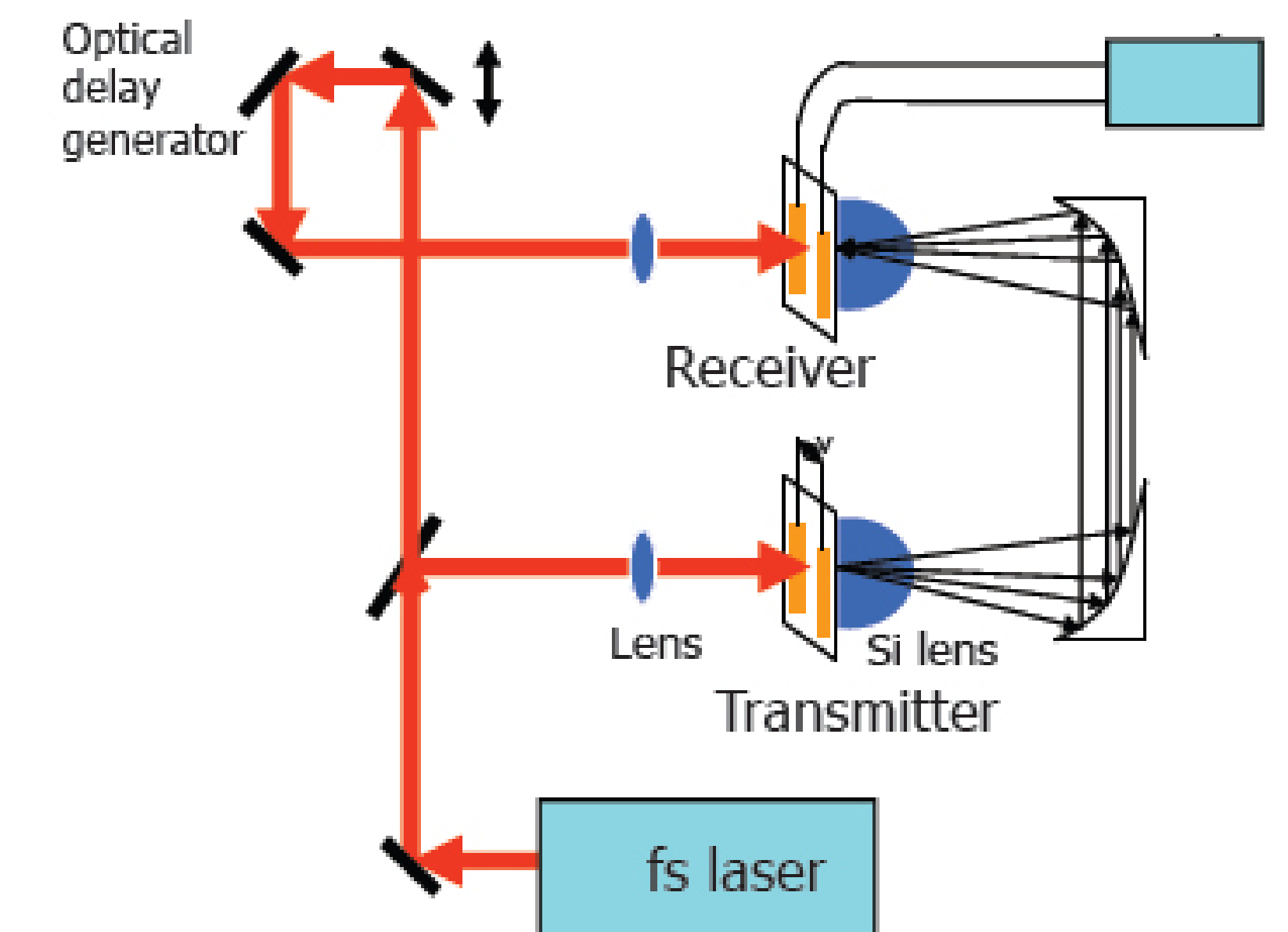


## HALF-CYCLE PULSES

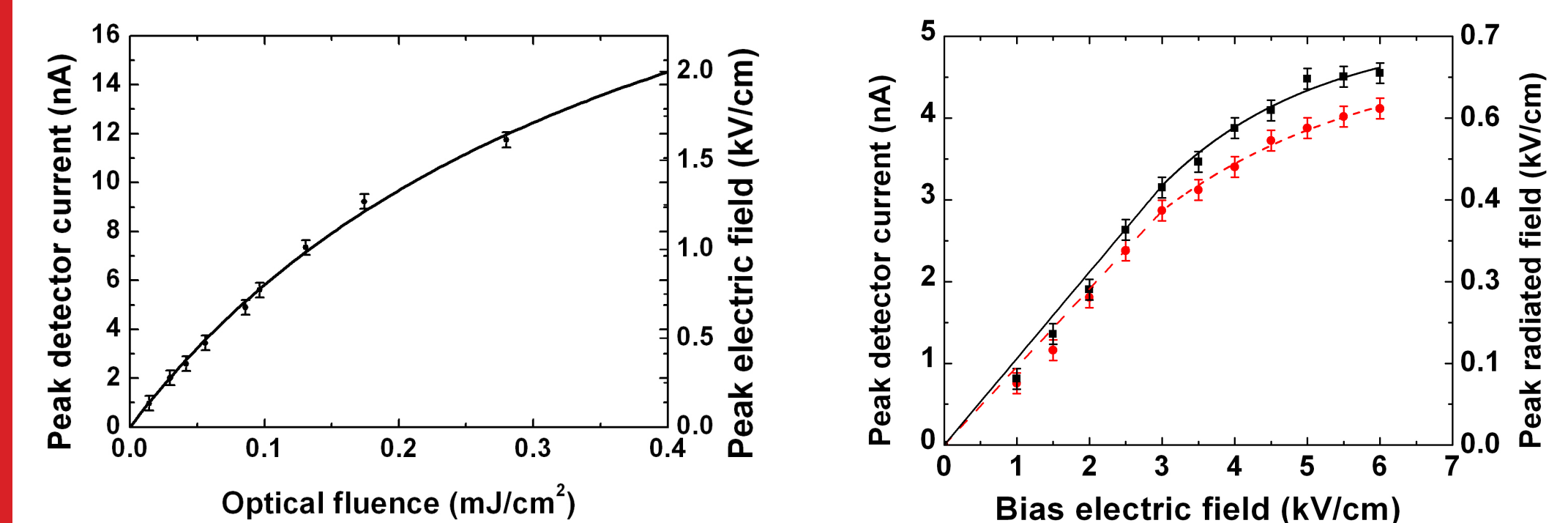
- Subpicosecond terahertz radiation is produced by gating a biased photoconductive (PC) antenna with ultrafast laser pulses<sup>5</sup>.
- Electrons are produced in conduction band when the photon energy is greater than the semiconductor band gap (1.43 eV in GaAs).
- The bias field accelerates these electrons and a photocurrent is produced that will decay with a time constant set by the carrier lifetime.
- A subpicosecond electromagnetic transient is emitted from the accelerating charge in the photocurrent.



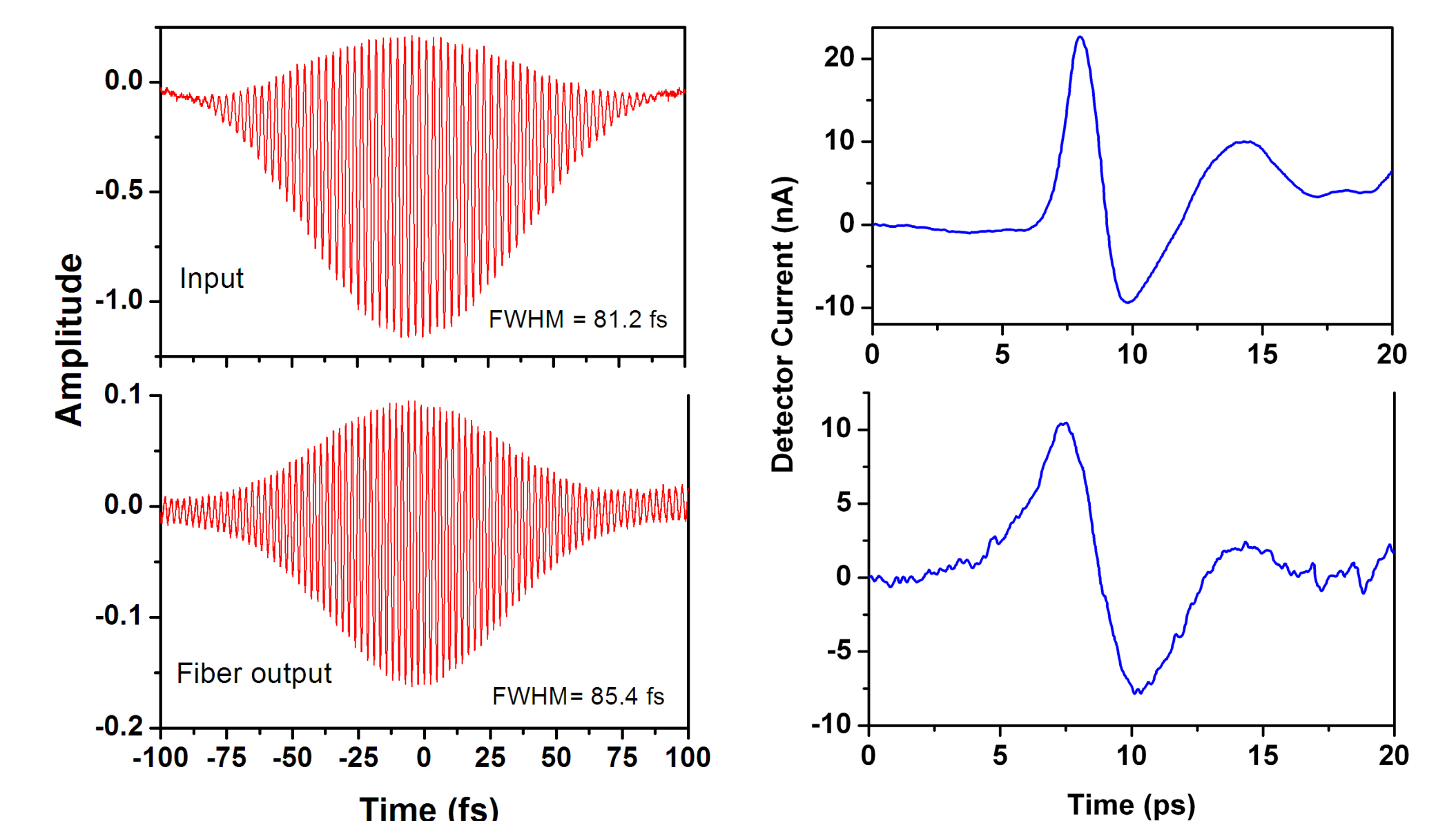
Antennas are fabricated using photolithography of aluminum onto a semi-insulating GaAs substrate.



Our half cycle pulse generation and detection test bed is shown schematically above. A femtosecond laser beam is split into two parts to pump the transmitter and the detector. The detector bias voltage is electrically chopped at a few kilohertz to allow for lock-in detection.



The terahertz output power is linear until saturation for both (a) bias electric field across the SI-GaAs wafer and (b) pump laser power.



Comparison between Autocorrelation signals of Oscillator output and the fiber output

Comparison between THz generation by Oscillator output and the fiber output

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