Ultrafast, broadband and tunable THz reflector based on high resistivity silicon.

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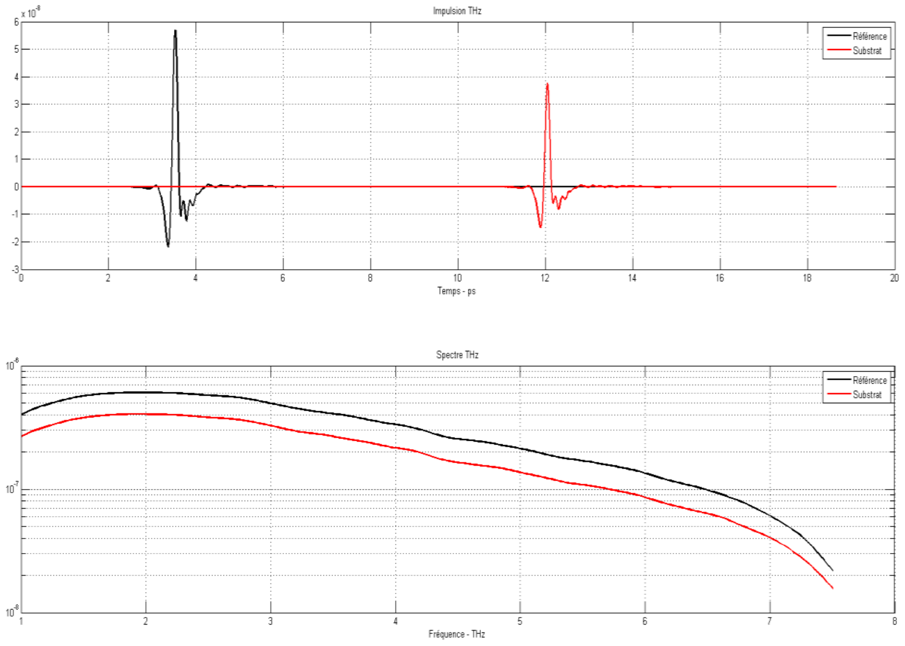
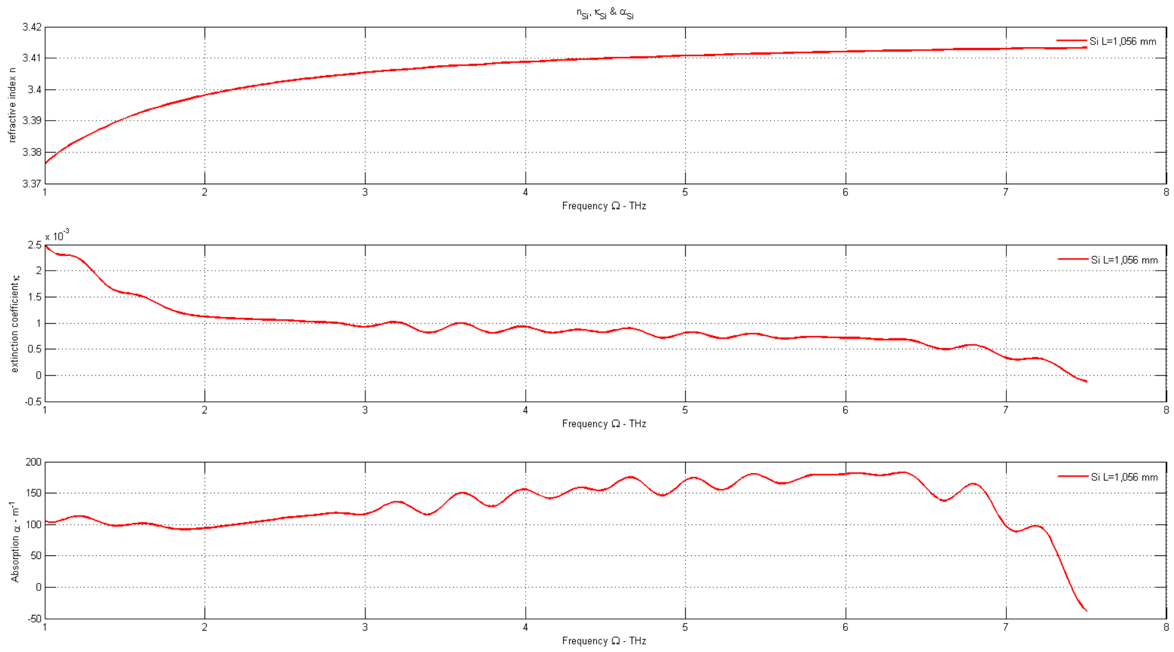
Introduction

- Silicon is of upmost importance in electronic
- The control of defects and free carriers strongly impacts its performance.
- Nowadays, large silicon wafers with less than 10^{13} cm^{-3} doping concentration exhibit high resistivity ~1000 Ω.cm.
- Such high resistivity silicon (HRSi) substrates have very low absorption: *below 3 THz a 1 mm thick HRSi substrate as an O.D.<0.01*.
- They are often used as a low cost dichroic filter to reflect above Si bandgap radiation and transmit THz radiations.
- Hereafter we demonstrate they can also be used as ultrafast, broadband and tunable THz reflectors or density filters.

TDS-THz spectroscopy of the studied HRSi wafer

Experiment performed in transmission at normal incidence

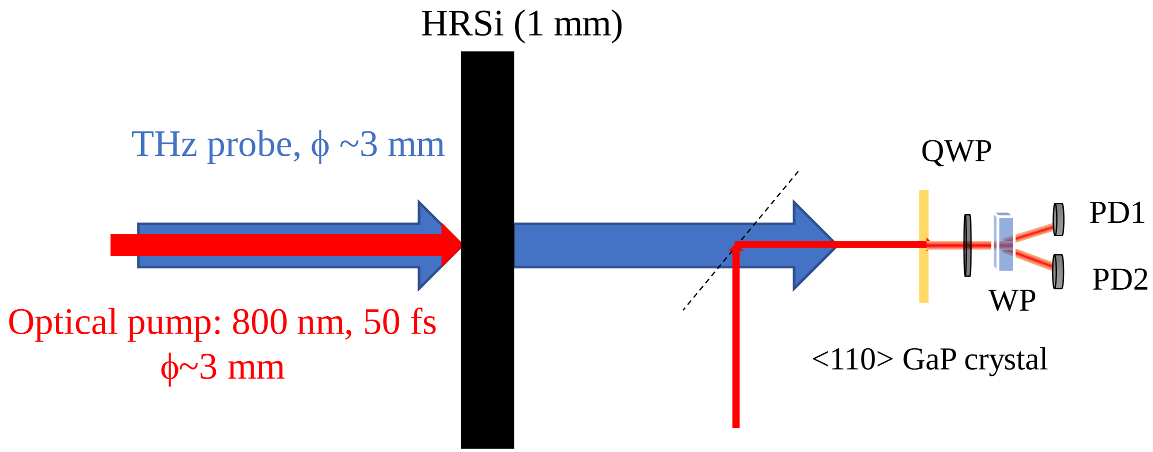




- As the frequency increases, the index slightly increases from 3.378 (1 THz) to 3.412 (7 THz)
- Absorption is almost constant κ~0.01 cm^{-1} from 1 THz to 7 THz
- The transmission at the THz peak is T≈68% in good agreement with the tabulated value T≈70%

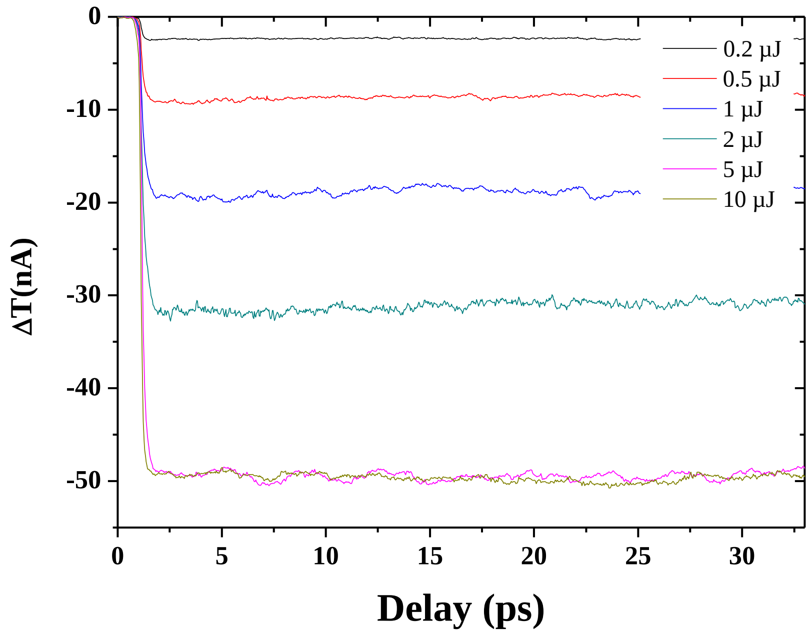
Optical-pump THz probe experiments in transmission at 0°

Sketch of the experimental set-up



Result

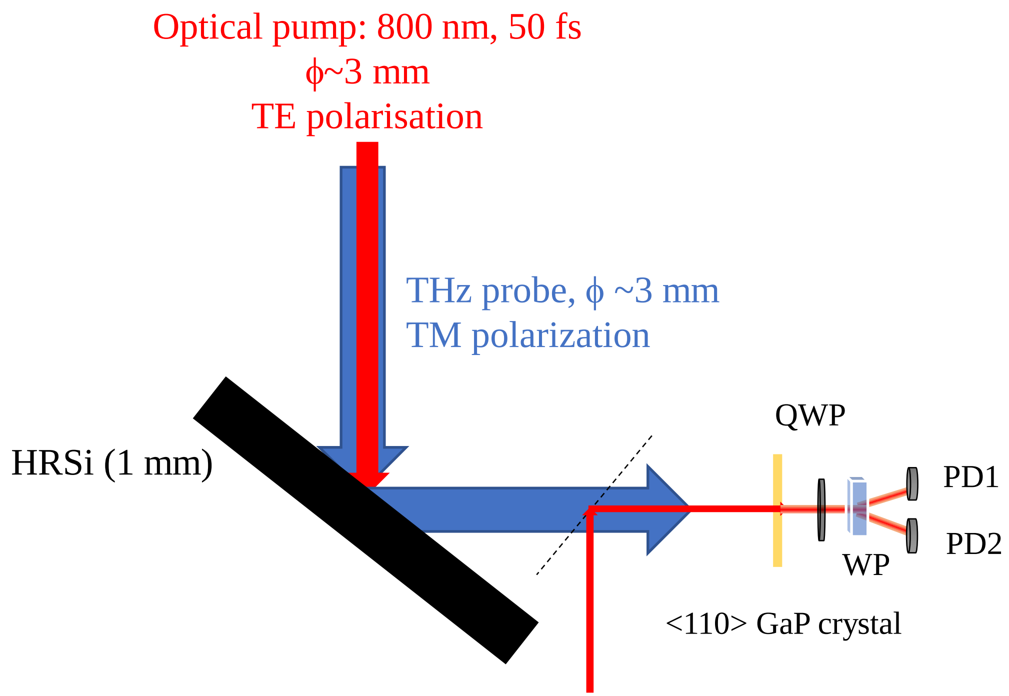
- **The THz pulse is sampled at its maximum**
- **The pump is delayed with resect to the THz pulse**



After 1 ps and above 10 μJ of pump the transmission of the THz pulse < 10%!

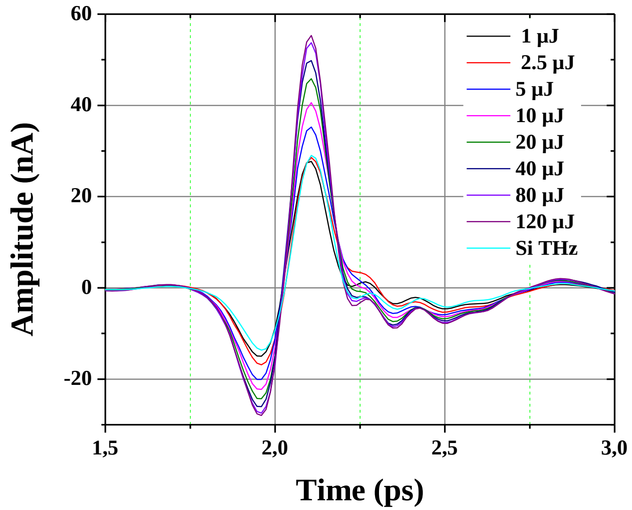
Optical-pump THz probe experiments in reflection at 45°

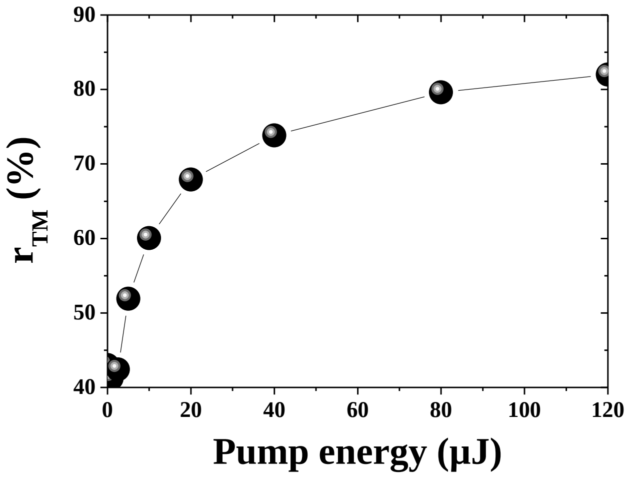
Sketch of the experimental set-up



Result

- The pump pulse hits HRSi 10 ps before been sensed by the THz pulse





The reflection coefficient for the electric field increases up to 85% !

Model for index variation induced by photo-carriers in HRSi

- The pump pulse is absorbed and generates N(E) carriers in HRSi within the absorption length l_{abs} (~10 µm at 800 nm)

$$\mathrm{N(E)} \approx T\alpha \frac{E\lambda}{hc}\frac{4}{\pi l_{abs}\phi^2}$$

- T: transmission coefficient for the pump pulse
- α: absorption of pump within absorption length l_{abs}
- E: energy of the pump pulse
- Φ: beam diameter transmission
- λ: pump wavelength
- c: speed of light
- h: Plank's constant

Example: for ϕ=3 mm and λ= 800 nm   * **N(1 µJ) ~2.5 10^{22} m^{-3}**   * **N(100 µJ) ~ 2.5 10^{24} m^{-3}**

- The generated carriers modify the dielectric constant

$$\varepsilon(\omega) = \varepsilon_{HRSi}(\omega) - \frac{\omega_p^2}{\omega(\omega+i\Gamma)} \quad \text{where } \omega_p^2 = \frac{N(E)e^2}{\varepsilon_0 m^*}$$

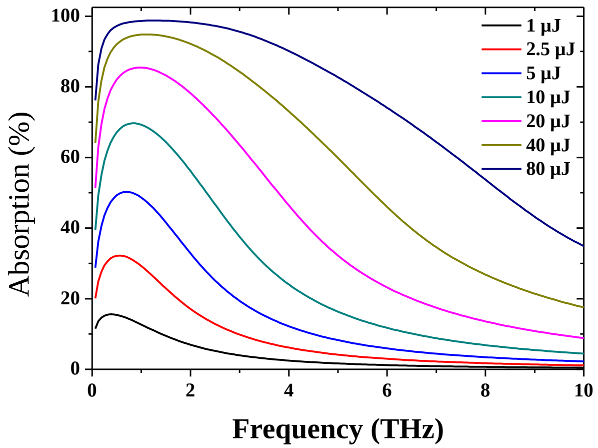
- e and m^* are the charge an reduced mass of the electron, respectively

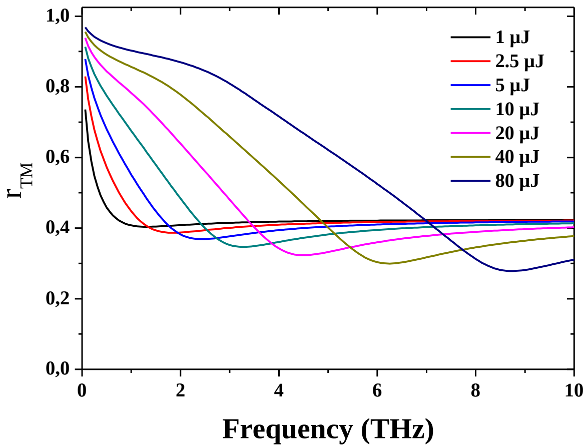
- In turn, this results in a change of the reflection coefficient and absorption constant

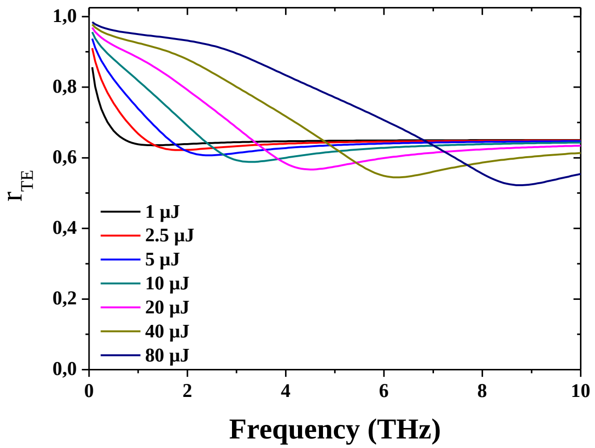
$$r_{TE}(\omega) = \frac{\cos(\theta) - \sqrt{\varepsilon(\omega) - \sin^2(\theta)}}{\cos(\theta) + \sqrt{\varepsilon(\omega) - \sin^2(\theta)}} \quad \text{and} \quad r_{TM}(\omega) = \frac{-\varepsilon(\omega)\cos(\theta) + \sqrt{\varepsilon(\omega) - \sin^2(\theta)}}{\varepsilon(\omega)\cos(\theta) + \sqrt{\varepsilon(\omega) - \sin^2(\theta)}}$$

Comparison experiment-theory

- **Results of the numerical simulations at θ=45° of incidence with beam diameter of 3 mm**

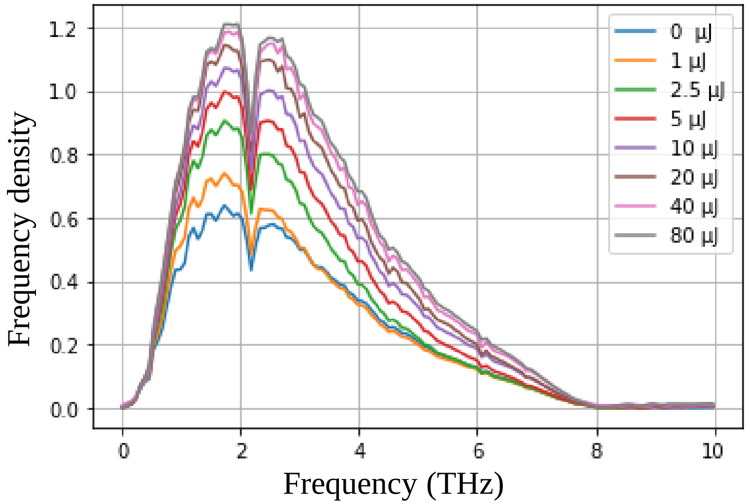




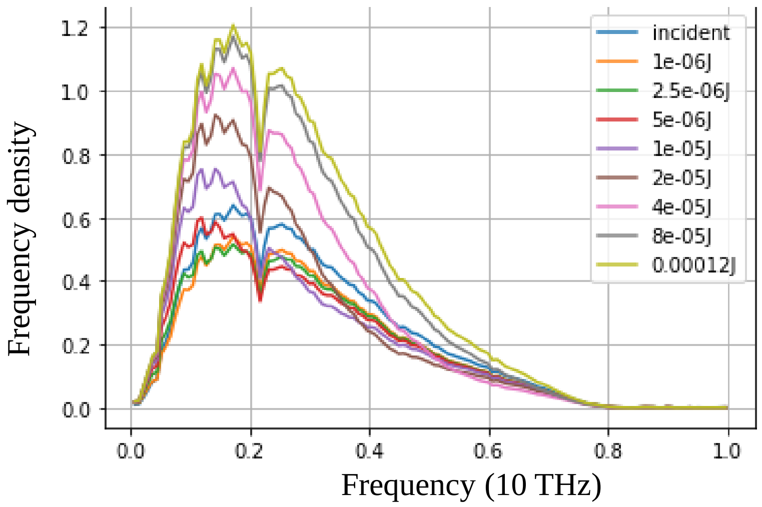


- **Comparison with experiment**

Experiment (TM polarization)

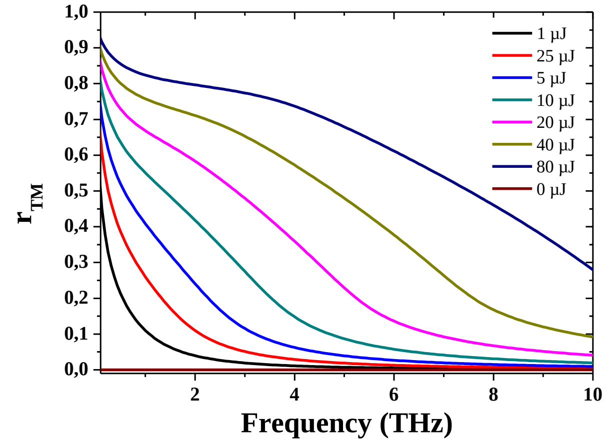


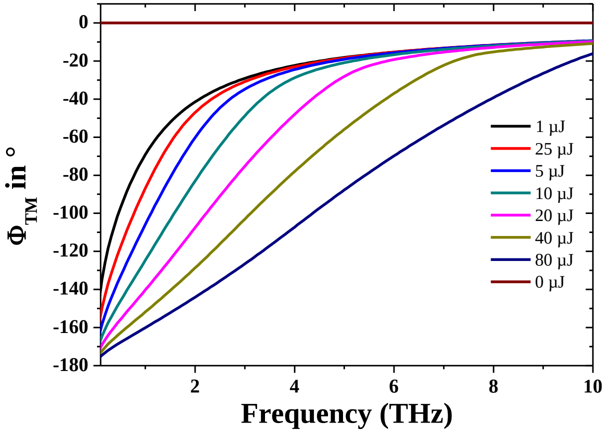
Theory (TM polarization)

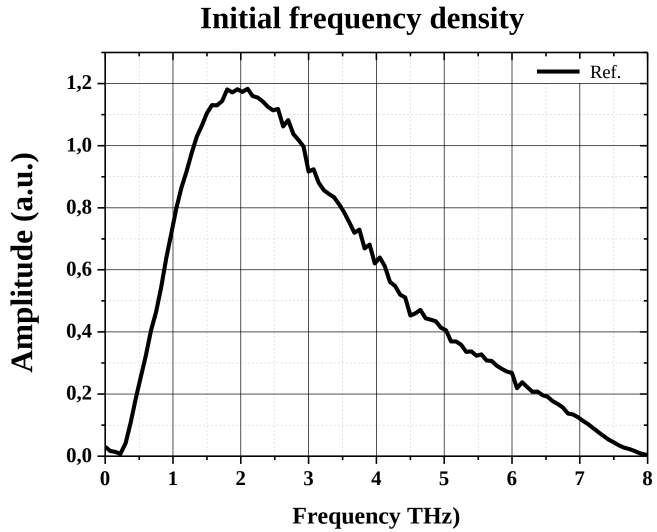


Evolution of the reflection coefficient at Brewster's angle

- The pump and THz are collinear, TM polarized, focused on a beam spot of ~7 mm^2 with θ_{inc} ~73.4° on HRSi

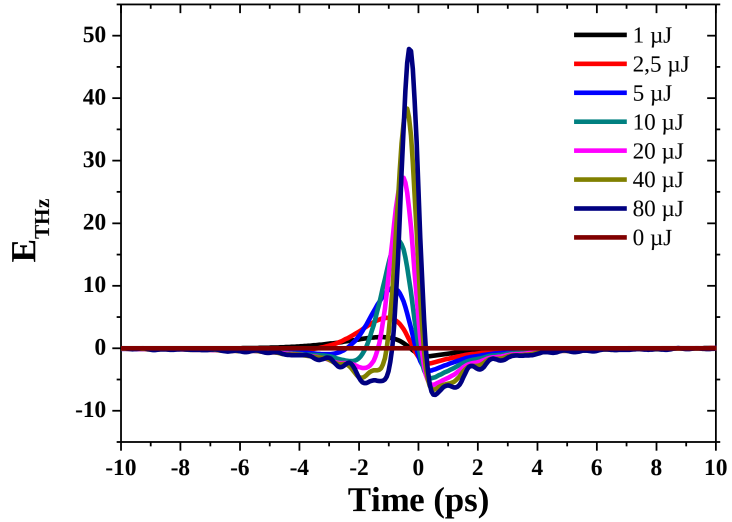






FFT

Considering all the spectral components are initially in phase



- **With 80 µJ pump pulse and within 1 ps, one can modulate r_{TM} from 0 to ~80% in between 0 and 4 THz !**
- **But since r_{TM} is a complex number, the temporal shape of the THz pulse is expected to be modified**

Conclusions

- **We have study the evolution of the transmission and reflection coefficient of a THz pulse on HRSi substrate upon excitation by an amplified femtosecond Ti:Sapphire laser pulse.**

- **We have experimentally shown that the transmission and reflection coefficients can be largely, efficiently and rapidly modulated by the pump pulse.**

- **A simple model where carriers generated by the pump pulse well accounts for the observed phenomena.**

- **This model indicates that at Brewster’s angle and for TM polarized optical pump, one will be able to modulate the reflection coefficient of a THz pulse from 0 up to 80% in the 0-4 THz spectral range.**

- **We have shown the temporal shape of the reflected pulse should also be modified.**

- **This study also indicates that HRSi can also be used as ultrafast, broadband and tunable density filter.**