Time Refraction

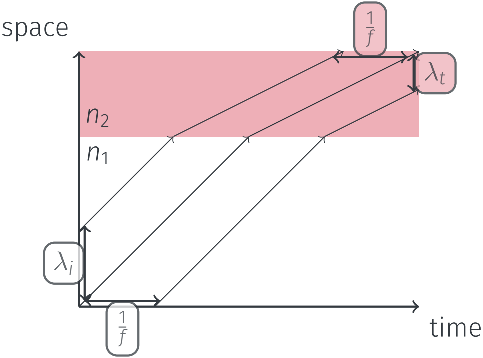
Exploring Models for Time-Dependent Refractive Index Materials and Confirming the Temporal Snell's Law of Time-Refraction with Finite-Difference Time-Domain Simulations

Ryan Alexander
Supervisor: Dr. Daryl Beggs

School of Physics and Astronomy, Cardiff University

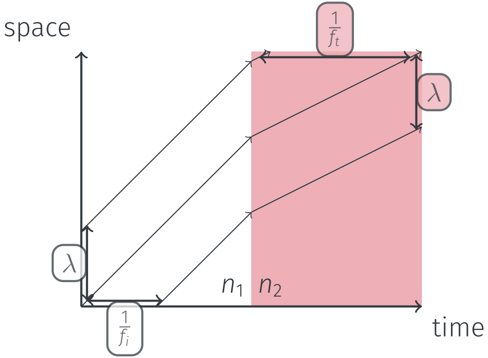
Time Refraction and the Temporal Snell's Law

Spatial Refraction



[1]

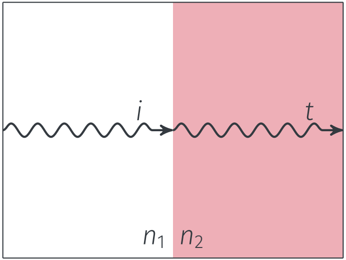
Temporal Refraction



[1]

The Temporal Snell's Law

$$\mathbf{E}_i(\mathbf{r}, t) = \exp\left[i\left(\mathbf{k}\cdot\mathbf{r} - 2\pi f_i t\right)\right]$$
$$\mathbf{E}_t(\mathbf{r}, t) = \exp\left[i\left(\mathbf{k}\cdot\mathbf{r} - 2\pi f_t t\right)\right]$$



$$k = 2\pi f n / c \implies f_i n_1 = f_t n_2$$

Verifying this law was the main aim of this project.

[2]

How to Physically Change Refractive Index

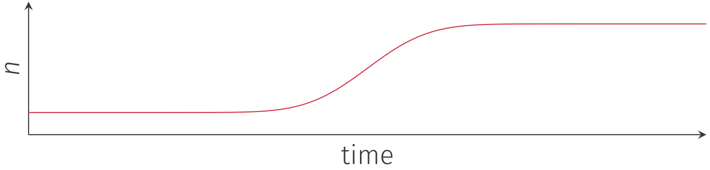
Ultrafast Optics

- Light travels through one millimeter of material on the order of 10^{-12} (pico) seconds.
- Hence, in practically sized materials, refractive index must change on the picosecond order ("ultrafast" order).

Free Carrier Dispersion

$$\Delta n = \frac{-e^2\lambda^2}{8\pi^2 c^2 \varepsilon_0 n_1} \left(\frac{N_e}{m^*_{ce}} + \frac{N_h}{m^*_{ch}} \right)$$

- Δn is proportional to concentration of free carriers which can be injected at ultrafast rates.
- Unfortunately, absorptivity also increases with free carriers.
- Carriers decay on the nanosecond order. Excitation ($n_1 \rightarrow n_2$) is far quicker than decay ($n_2 \rightarrow n_1$) and Δn follows an **error function**.

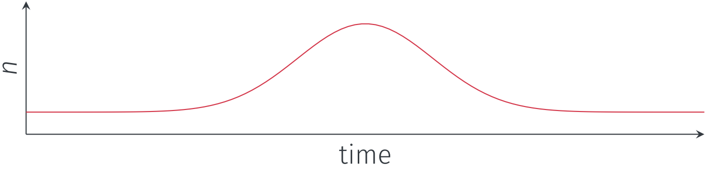


[3]

The Optical Kerr Effect

$$\Delta n = \frac{3\chi^{(3)}}{4n_1^2\varepsilon_1 c} I$$

- Δn is proportional to the intensity of incident light.
- Gaussian laser pulses are used, hence Δn follows a **Gaussian function**.



[4]

Previous Demonstrations

- **Free Carrier Dispersion**: Shifts have been limited to $\Delta f/f_i \approx 0.1\%$ because of high absorptivity [5, 6, 7].
- **The Optical Kerr Effect**: Shifts have been limited to $\Delta f/f_i \approx 1\%$ because of low $\chi^{(3)}$ [8, 9, 10, 11, 12, 13, 14].

Epsilon-Near-Zero Materials

nature COMMUNICATIONS

ARTICLE

Check for updates

https://doi.org/10.1038/s41467-020-15682-2 OPEN

Broadband frequency translation through time refraction in an epsilon-near-zero material

Yiyu Zhou [1,4✉], M. Zahirul Alam[2,4], Mohammad Karimi[2], Jeremy Upham[2], Orad Reshef [2], Cong Liu [3], Alan E. Willner[3] & Robert W. Boyd [1,2]

$\varepsilon \ll 1$ materials allow for the amplification of Δn in the optical Kerr effect.

$$\Delta n = \frac{3\chi^{(3)}}{4n_1^2\varepsilon_1 c} I$$

They achieved $\Delta f / f_i \approx 6\%$.

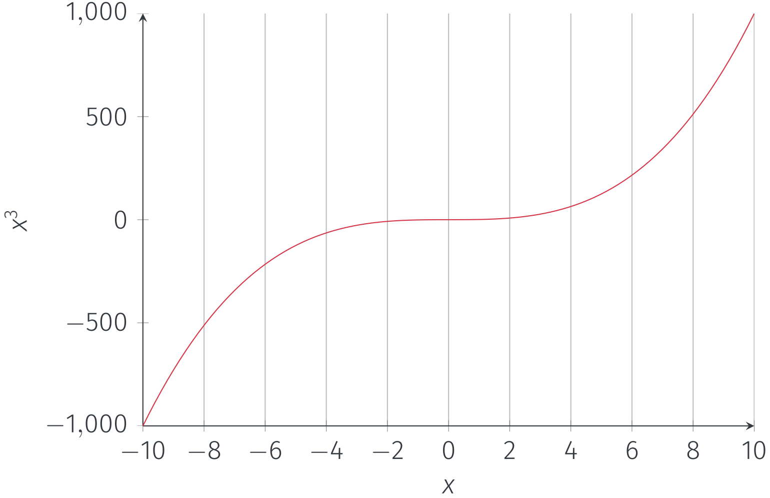
Could be used in **photonic circuits** e.g. multiplexing signals for communications.

[1]

Finite-Difference Time-Domain Simulations

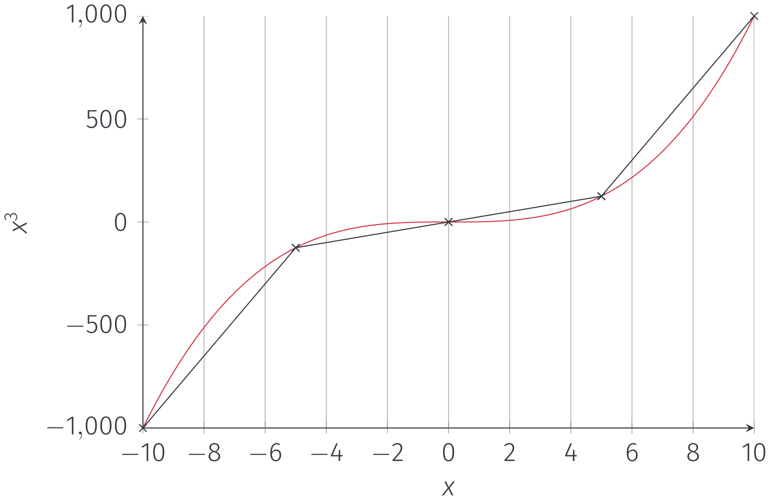
The Finite-Difference Method

Maxwell's equations can not be solved analytically in most cases. Therefore, a numerical way of approximating solutions is needed.



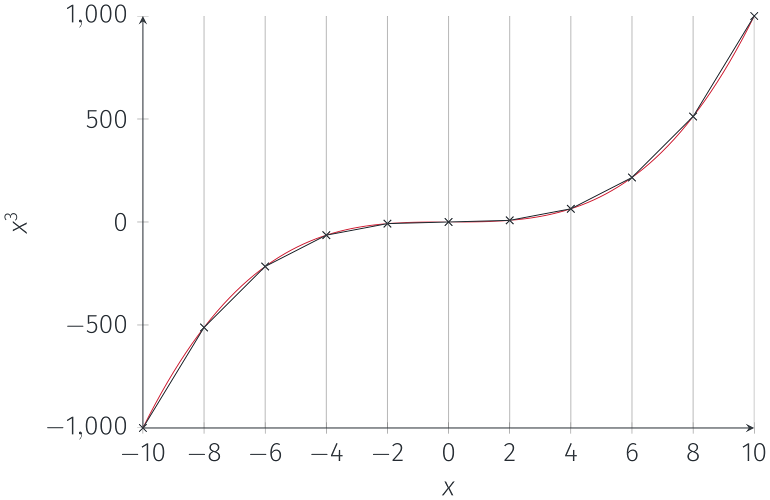
The Finite-Difference Method

Maxwell's equations can not be solved analytically in most cases. Therefore, a numerical way of approximating solutions is needed.



The Finite-Difference Method

Maxwell's equations can not be solved analytically in most cases. Therefore, a numerical way of approximating solutions is needed.



Finite-Difference Time-Domain for Solving Maxwell's Equations

Electromagnetic waves evolve according to Maxwell's differential equations.

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu_0}\frac{\partial E_y}{\partial x}$$

A computer can solve these equations with the finite-difference time domain method and propagate the fields through time:

$$H_z(t_{n+2}, x_k) = H_z(t_n, x_k) - \frac{\Delta t}{\mu_0 \Delta x}\left[E_y\left(t_{n+1}, x_{k-1}\right) - E_y\left(t_{n+1}, x_{k+1}\right)\right]$$

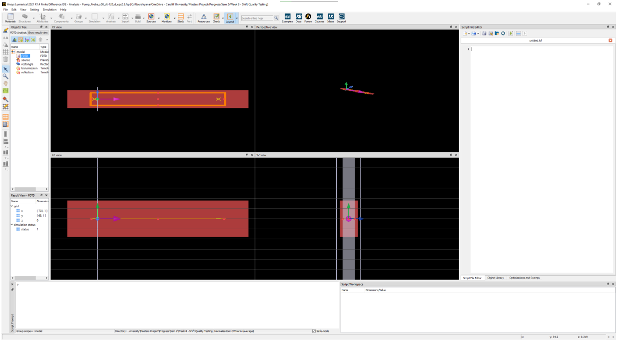
t_{n+2} t_n t_{n+1}

Infinitesimal Δt and Δx would give analytical solutions.

[15]

Lumerical FDTD

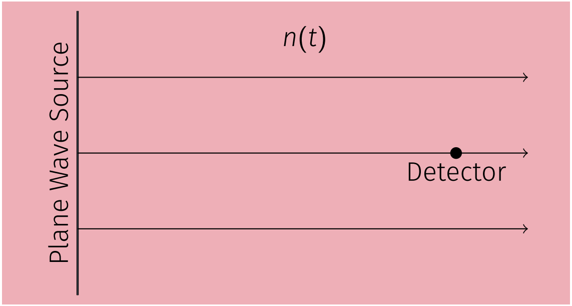
$$H_z(t_{n+2}, x_k) = H_z(t_n, x_k) - \frac{\Delta t}{\mu_0 \Delta x}\left[E_y\left(t_{n+1}, x_{k-1}\right) - E_y\left(t_{n+1}, x_{k+1}\right)\right]$$



Lumerical FDTD simulates light propagating from sources and through materials by solving these equations.

Pump-Probe Experiments

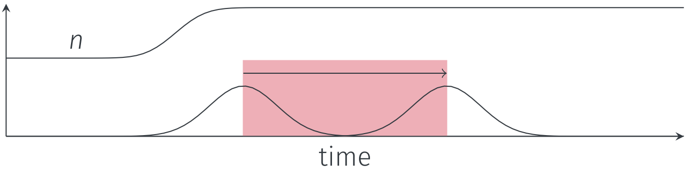
Simulation Setup



$$f_i n_1 = f_t n_2$$

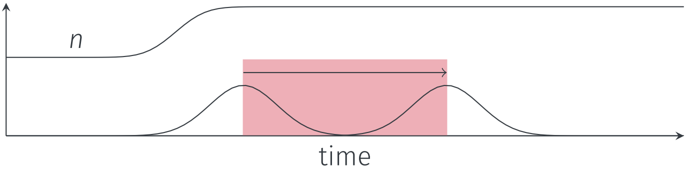
Demonstrating a Frequency Shift (Error Function)

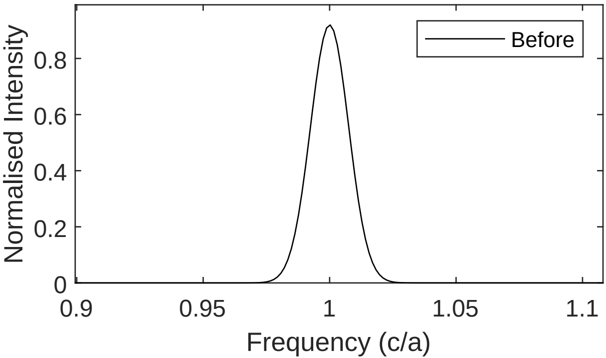
Frequency Shift



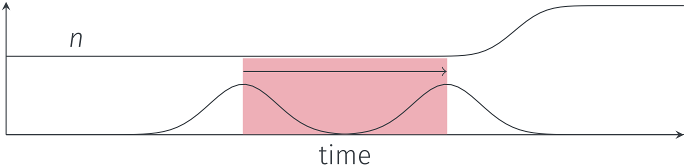
$$f_i n_1 = f_t n_2$$

Frequency Shift



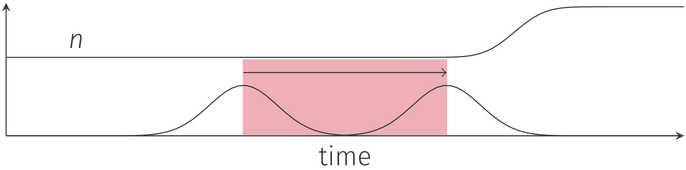


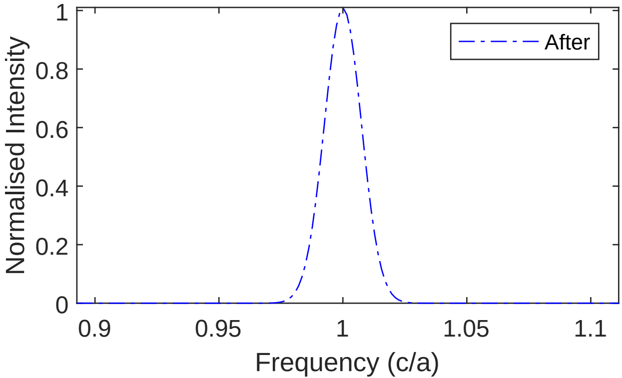
Frequency Shift



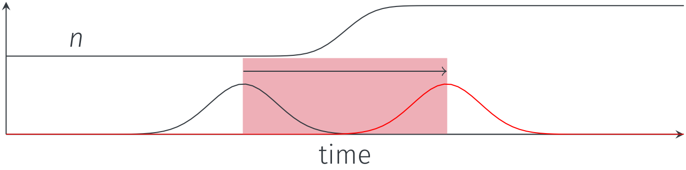
$$f_i n_1 = f_t n_2$$

Frequency Shift



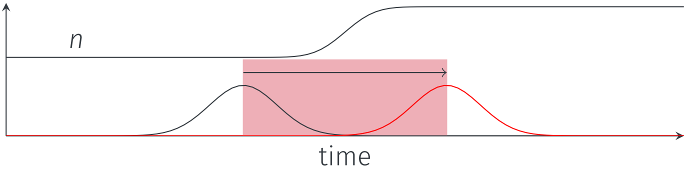


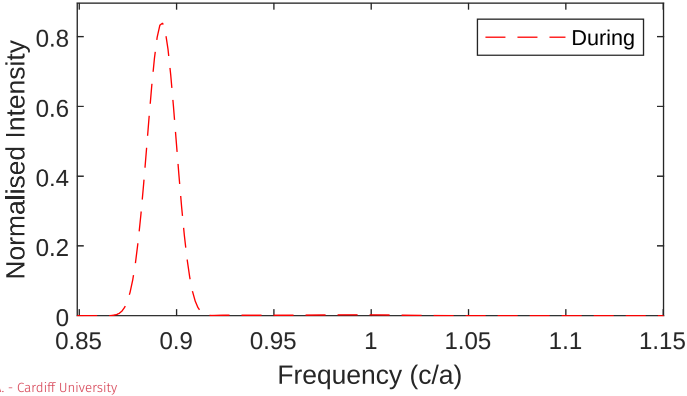
Frequency Shift



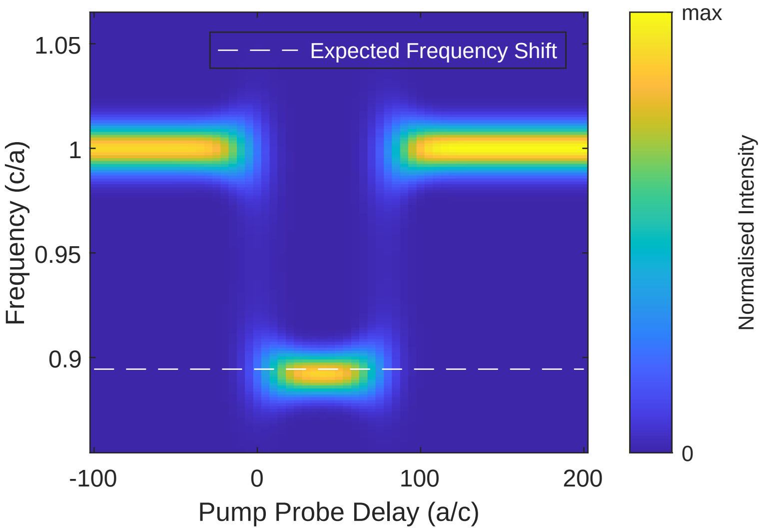
$$f_i n_1 = f_t n_2$$

Frequency Shift



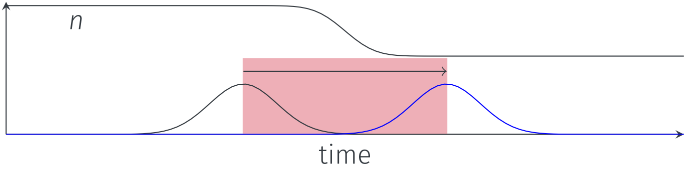


Frequency Shift



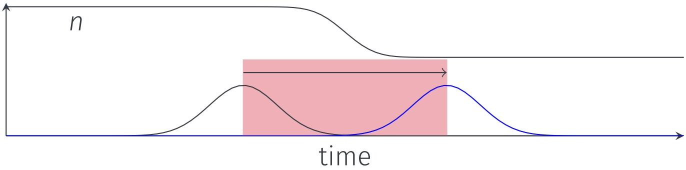
Demonstrating a Positive Frequency Shift (Error Function)

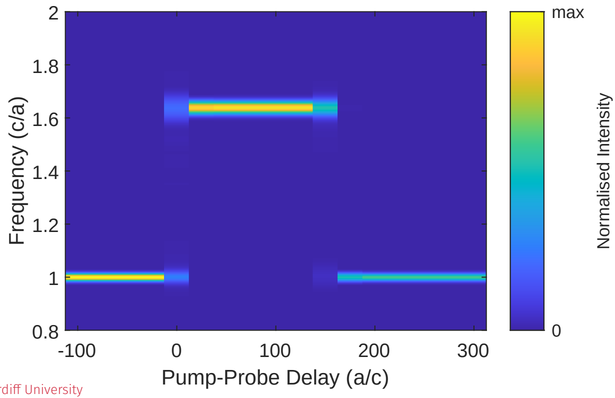
Positive Frequency Shift



$$f_i n_1 = f_t n_2$$

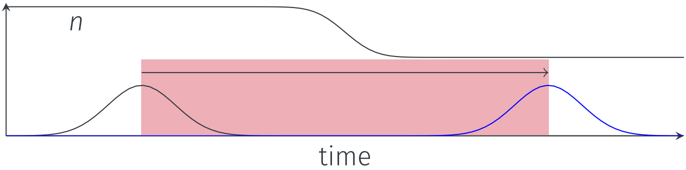
Positive Frequency Shift



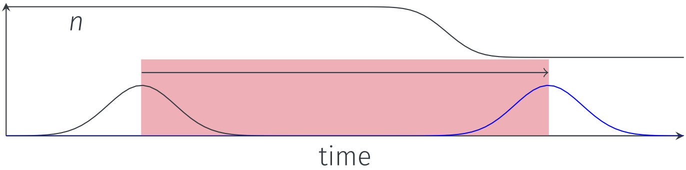


Varying Simulation Width (Error Function)

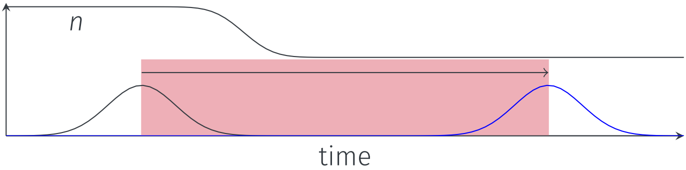
Varying Simulation Width



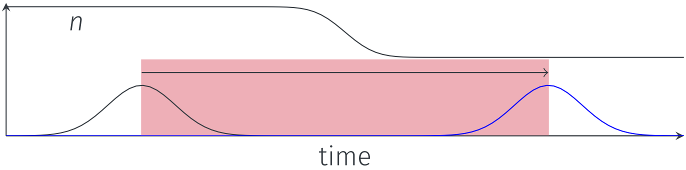
Varying Simulation Width

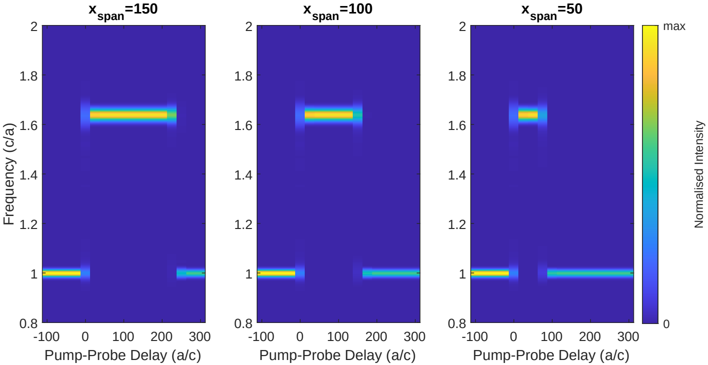


Varying Simulation Width



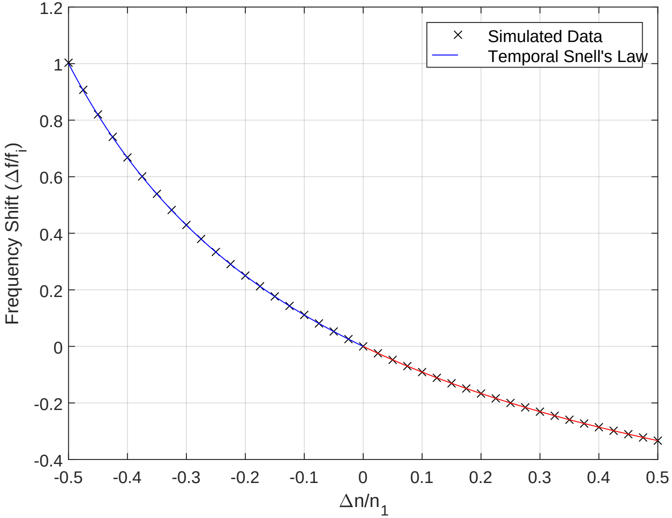
Varying Simulation Width





Testing the Temporal Snell’s Law (Error Function)

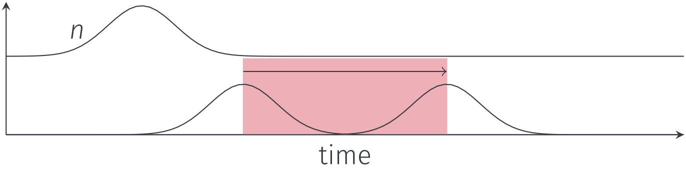
Testing the Temporal Snell's Law



$f_i n_1 = f_t n_2 \rightarrow$ 99.8% agreement!

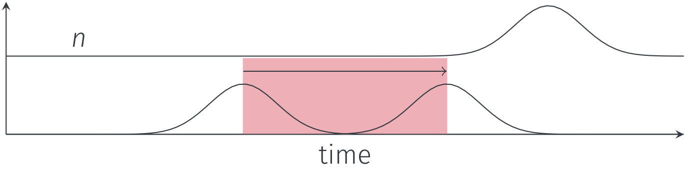
Gaussian Function Results

Frequency Shift



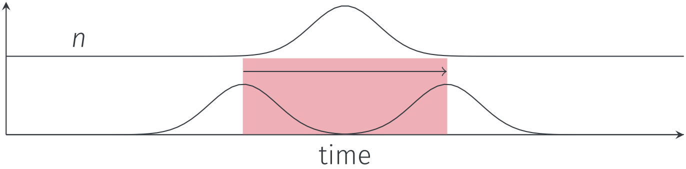
$$f_i n_1 = f_t n_2$$

Frequency Shift



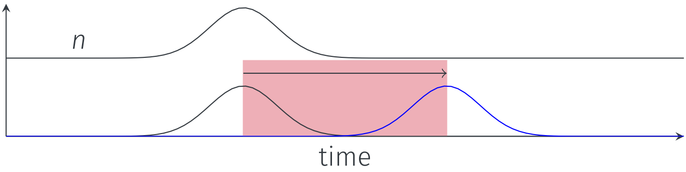
$$f_i n_1 = f_t n_2$$

Frequency Shift



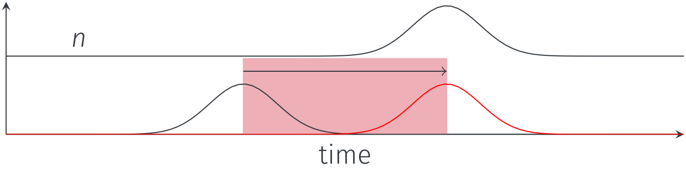
$$f_i n_1 = f_t n_2$$

Frequency Shift



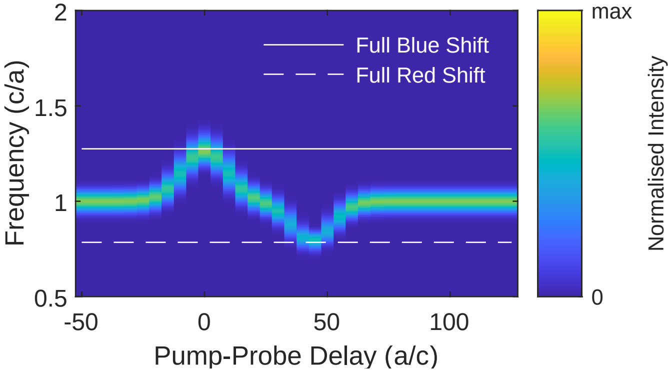
$$f_i n_1 = f_t n_2$$

Frequency Shift



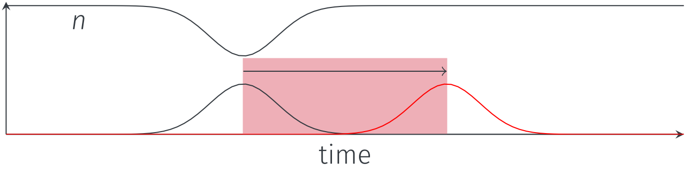
$$f_i n_1 = f_t n_2$$

Frequency Shift



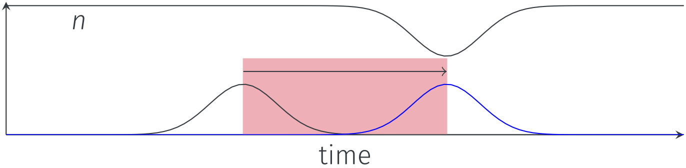
$$f_i n_1 = f_t n_2$$

Negative n Shift



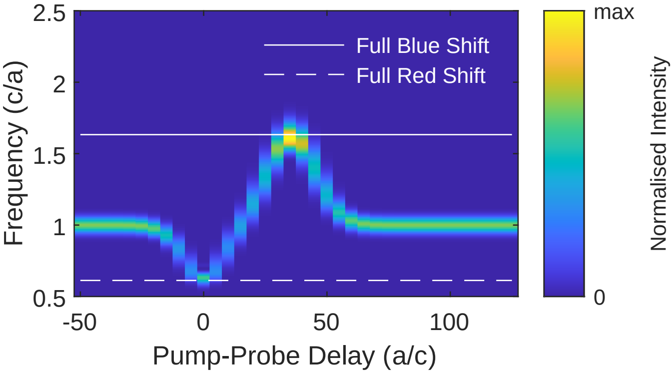
$$f_i n_1 = f_t n_2$$

Negative n Shift



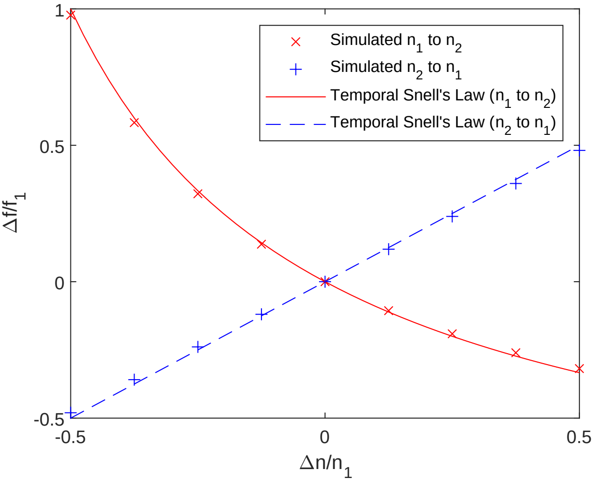
$$f_i n_1 = f_t n_2$$

Negative n Shift



$$f_i n_1 = f_t n_2$$

Testing the Temporal Snell's Law



$f_i n_1 = f_t n_2 \rightarrow$ 96% agreement

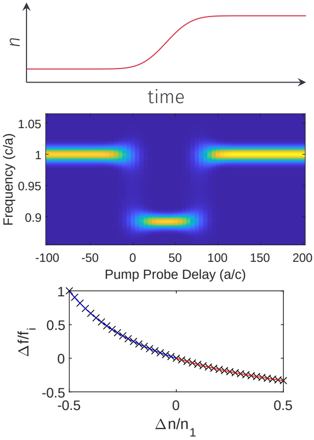
Conclusions

Conclusions

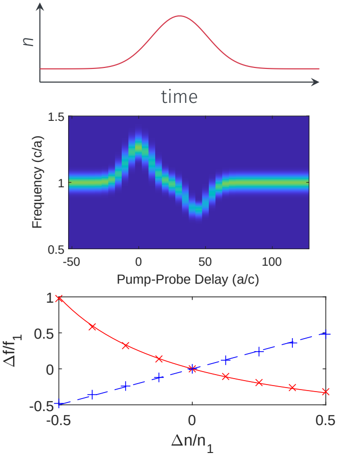
Exploring Models for Time-Dependent Refractive Index Materials and Confirming the Temporal Snell's Law of Time-Refraction with Finite-Difference Time-Domain Simulations

$$f_i n_1 = f_t n_2$$

Free Carrier Dispersion - 99.8% Agreement



Optical Kerr Effect - 96% Agreement



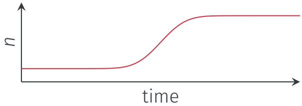
Questions?

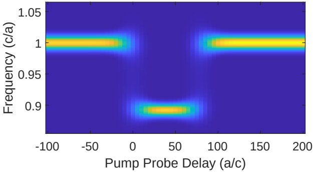
Conclusions

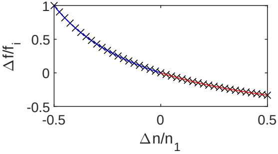
Exploring Models for Time-Dependent Refractive Index Materials and Confirming the Temporal Snell's Law of Time-Refraction with Finite-Difference Time-Domain Simulations

$$f_i n_1 = f_t n_2$$

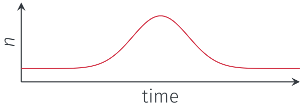
Free Carrier Dispersion - 99.8% Agreement

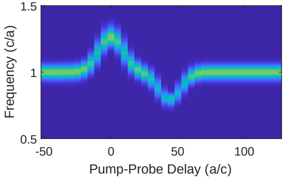


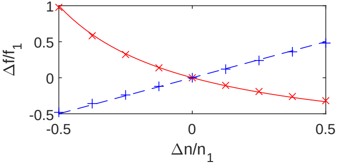




Optical Kerr Effect - 96% Agreement







References

[1] Yiyu Zhou et al. "Broadband frequency translation through time refraction in an epsilon-near-zero material". In: *Nature communications* 11.1 (2020), pp. 1–7.

[2] JT Mendonça and PK Shukla. "Time refraction and time reflection: two basic concepts". In: *Physica Scripta* 65.2 (2002), p. 160.

[3] Graham T Reed and Andrew P Knights. *Silicon photonics: an introduction*. John Wiley & Sons, 2004, p. 101.

[4] Robert W Boyd and Debbie Prato. *Nonlinear Optics*. eng. San Diego: Elsevier Science & Technology, 2008, pp. 207–210. ISBN: 0123694701.

[5] M Castellanos Muñoz, A Yu Petrov, and M Eich. “All-optical on-chip dynamic frequency conversion”. In: *Applied Physics Letters* 101.14 (2012), p. 141119.

[6] Tobias Kampfrath et al. “Ultrafast adiabatic manipulation of slow light in a photonic crystal”. In: *Physical Review A* 81.4 (2010), p. 043837.

[7] Jeremy Upham et al. “On-the-fly wavelength conversion of photons by dynamic control of photonic waveguides”. In: *Applied physics express* 3.6 (2010), p. 062001.

[8] Govind P Agrawal, PL Baldeck, and RR Alfano. “Temporal and spectral effects of cross-phase modulation on copropagating ultrashort pulses in optical fibers”. In: *Physical Review A* 40.9 (1989), p. 5063.

[9] Jie Li et al. "OTDM add-drop multiplexer based on XPM-induced wavelength shifting in highly nonlinear fiber". In: *Journal of lightwave technology* 23.9 (2005), p. 2654.

[10] P Mehta et al. "Ultrafast wavelength conversion via cross-phase modulation in hydrogenated amorphous silicon optical fibers". In: *Optics express* 20.24 (2012), pp. 26110–26116.

[11] R Dekker et al. "Ultrafast Kerr-induced all-optical wavelength conversion in silicon waveguides using 1.55 μm femtosecond pulses". In: *Optics express* 14.18 (2006), pp. 8336–8346.

[12] K Kondo and T Baba. "Dynamic wavelength conversion in copropagating slow-light pulses". In: *Physical review letters* 112.22 (2014), p. 223904.

[13] Alejandro M Yacomotti et al. "Nonadiabatic dynamics of the electromagnetic field and charge carriers in high-Q photonic crystal resonators". In: *Physical review letters* 96.9 (2006), p. 093901.

[14] Stefan F Preble, Qianfan Xu, and Michal Lipson. "Changing the colour of light in a silicon resonator". In: *Nature Photonics* 1.5 (2007), pp. 293–296.

[15] Dennis M Sullivan. *Electromagnetic simulation using the FDTD method*. John Wiley & Sons, 2013.