Frequency combs via plasmonic resonances in time-dependent graphene lattices

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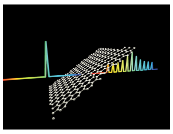
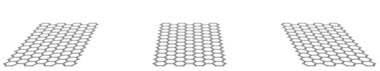
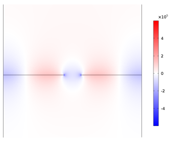
Frequency comb generation in graphene

Principle : when monochromatic light is sent on a graphene sheet with a time-dependent conductivity, a frequency comb is genarated in transmission [1]



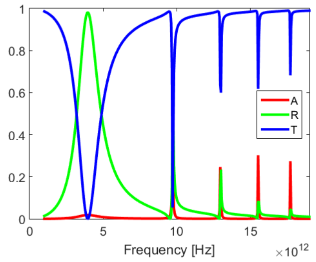
Here, we exploit plasmonic resonances of graphene lattices [2] to generate frequency combs



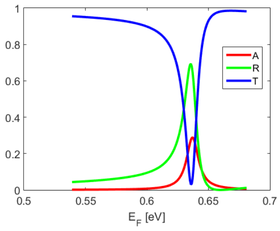


Simulation results

Transmission spectrum of a graphene grating. Each dip in the transmission corresponds to a plasmonic resonance that can be used in the CMT model.

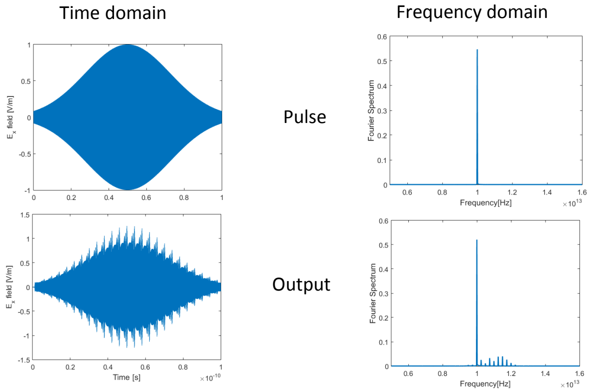


These resonances can be tuned by choosing the graphene doping level :



In our simulations, the doping level of the graphene grating is time dependent.

Our simulations are in the time domain. We send a monochromatic pulse trough a graphene grating and generate a frequency comb in the output.



The separation between the peaks of the comb is exactly the frequency of the modulation applied to th graphene grating. The width of the comb is linked to the strength of the modulation.

Conclusion

We studied a way to generate frequency combs using plasmonic resonances in time-dependant graphene gratings. These combs are widely tunable and can be scaled by controlling the properties of the graphene grating. We also proposed an analytical model that describes the dynamic inside the cavity and is in good agreement with our simulations.

CMT Model

Resonances in cavities with small absorption can be described by Coupled Mode Theory (CMT) [3] :

$$\left.\begin{aligned}\frac{dA(t)}{dt} &= \left(j\omega_{res} - {}^{1}/_{\tau}\right) A(t) + d\, s_1(t)\\ s_2(t) &= \kappa\, A(t) + t\, s_1(t)\end{aligned}\right\}$$

Static case : fixed cavity resonance frequency ω_{res}

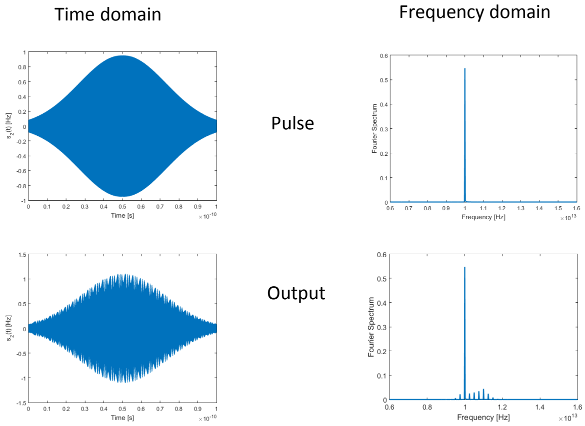
$$\left.\begin{aligned}\frac{dA(t)}{dt} &= \left(j\omega_{res}(\boldsymbol{t}) - {}^{1}/_{\tau}\right) A(t) + d\, s_1(t)\\ s_2(t) &= \kappa\, A(t) + t\, s_1(t)\end{aligned}\right\}$$

Dynamic case : graphene properties change in time and $\omega_{res}(t)$ becomes a function of time

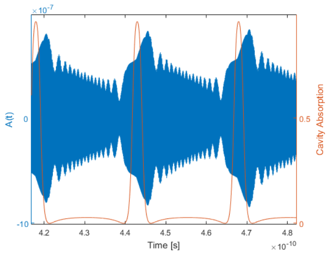
In this model, A is the energy inside the cavity, $s_1(t)$ the input, $s_2(t)$ the output, ${}^{1}/_{\tau}$ the damping rate, κ and d are coupling constants and t is the transmission without cavity.

Model results

Equations from the CMT model can be solved numerically. Using realistic parameters we obtain results similar to our simulations :



To understand the phenomena taking place, we look at the cavity dynamics :



The red curve is the instantaneous absorption coefficient of the cavity from the CMT theory.
The blue curve is a solution to CMT equations

When the cavity frequency matches the frequency of the incoming light, the absorption increases and energy goes inside the cavity.

2 step process :

- When the light enters the cavity, its frequency is ω_0. Once in the cavity, its frequency changes, following the modulation of $\omega_{res}(t)$.
- When the frequency of the incident light and the cavity don't match, the energy inside decays with the rate ${}^{1}/_{\tau}$.

References

[1] V. Ginis, P. Tassin, T. Koschny and C.M. Soukoulis, Tunable terahertz frequency comb generation using time-dependent graphene sheets, *Phys. Rev. B*, **91**, 161403(R) (2015)
[2] A. Yu. Nikitin, F. Guinea, F. J. Garcia-Vidal, and L. Martin-Moreno, Surface plasmon enhanced absorption and suppressed transmission in periodic arrays of graphene ribbons, *Phys. Rev. B*, **85**, 081405(R) (2012)
[3] S. Fan, W. Suh, and J. D. Joannopoulos, Temporal coupled-mode theory for the Fano resonance in optical resonators , *J. Opt. Soc. Am.* A20, 569-572 (2003)