PhD Title	**Reconfigurable nonlinear substrates for ultrafast plasmonics**
PhD Supervisor	Benoît Cluzel
Department	Photonics Department
Equipes	Near-field Optics group
Collaborations	P. NOE, CEA LETI, Grenoble (France) R. MARTINS, CHREA, Univ. Côte d'Azur (France)

Summary: In this PhD, we will aim at using **Epsilon Near Zero and Phase Change Materials** substrates for developing a **new class of ultrafast and reconfigurable plasmonic metasurfaces** operating at telecom wavelengths. In particular, our goal will be to **actively control the resonances of plasmonic nanodevices** by means of spatio-temporal shaping of light pulses.

The field of plasmonics permits the creation of devices operating at **ultrafast speeds with ultrasmall footprints and low energy consumption** when compared with conventional electronics and photonics. Recent advances in nanoscience and optics sprouted into the designing of nanoscale antennas operating at visible and Near Infra-Red (NIR) optical frequencies[1] being able to **confine fields in subwavelength regime**. The collective oscillations of the delocalized electrons in metallic nanostructures are defined as surface plasmons and have emerged as a **powerful tool with applications in various fields** including Raman Spectroscopy, fluorescence enhancement, analytics and sensing, photothermal therapy, (bio)-diagnostics and imaging[2]. One of the biggest motivations in plasmonics is the development and the functionality of an optical nanotransistor[3] to **pave the way to all-optical data processing with speeds that will surpass the gigahertz performance** of electronic components. Albeit versatile, plasmonic resonances have direct relation to the metallic geometry that must be pre-stablished to match a specific frequency. Not only the length and size are able to tune the resonances but also the dielectric surroundings have strong influence on the overall optical properties of nanoantennas[4,5]. In fact, substrates play a key role on plasmonic behaviors[6]. However, little attention has been paid to the role of substrates to the all-purpose physical phenomena involved and a **controllable substrate could be the key to tune on demand the field confinement and surface plasmon resonances in nanostructures**. Among the new materials which have been developed recently, nonlinear dielectrics such as **Epsilon Near-Zero (ENZ)** and **Phase Change Materials (PCM)** exhibit unusual physical properties available at telecom wavelengths with the promising to become the **next generation of ultrafast nanodevices platform**.

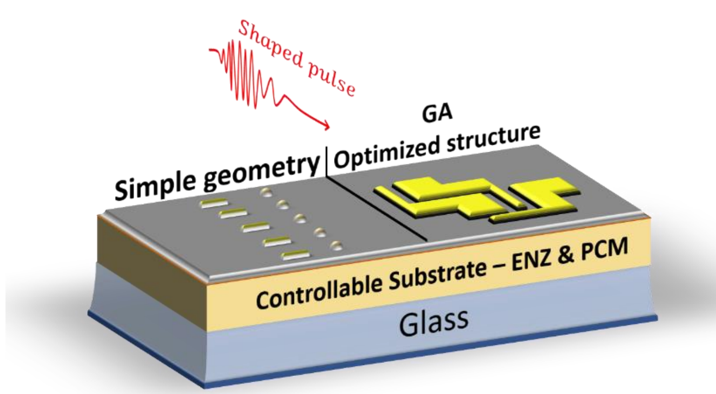

Figure 1 - Plasmonic controllable device – general concept. With the use of unconventional substrates – ENZ and PCM – and desired shapes; Left side – use of simple geometry; Right side. Optimized structure.

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[1] Giannini, V., et al. (2011). "Plasmonic nanoantennas: fundamentals and their use in controlling the radiative properties of nanoemitters." Chemical reviews **111**(6): 3888-3912.
[2] Sau, T. K., et al. (2010). "Properties and applications of colloidal nonspherical noble metal nanoparticles." Advanced Materials **22**(16): 1805-1825.
[3] Miller, D. A. (2010). "Are optical transistors the logical next step?" Nature Photonics **4**(1): 3.
[4] Mock, J. J., et al. (2003). "Local refractive index dependence of plasmon resonance spectra from individual nanoparticles." Nano letters **3**(4): 485-491.
[5] Neubrech, F., et al. (2006). "Resonances of individual metal nanowires in the infrared." Applied Physics Letters **89**(25): 253104.
[6] Zhang, S., et al. (2011). "Substrate-induced Fano resonances of a plasmonic nanocube: a route to increased-sensitivity localized surface plasmon resonance sensors revealed." Nano letters **11**(4): 1657-1663.

Thus, controlling their properties will shine a new light into designing metasurfaces.

On one hand, **ENZ materials** have very low permittivity in a specific frequency range which leads to **remarkable phenomena and effects** with applications in microscopy, all-optical data processing and quantum information [7,8]. In particular, **Alam and co-corkers[9] recently reported a large optical nonlinearity of Indium Tin Oxide (ITO)** operating at its ENZ region in NIR which can be controlled optically by means of femtosecond laser pulses. Last year, the same group has also reported a large optical nonlinearity of nanoantenas when coupled to an ENZ material[8] - in their work, they were able to register a nonlinear index of refraction as high as $-3.7\ cm^2GW^{-1}$ which is **6 orders of magnitude higher than the highest nonlinear crystals available commercially** such as BBO ($\sim 10^{-6} cm^2GW^{-1}$). This combination between plasmonic nanoantennas and ENZ substrate tackles a longstanding challenge in nonlinear optics: creating a **nonlinear material with its nonlinear index in the order of unity** enabling the development of ultrafast devices with high nonlinearity operating at very low power and small footprints.

On the other hand, **Phase Change Materials (PCM)** commonly used in data storage technologies exhibits up to **200% change in the index of refraction** as their internal phase changes from amorphous to crystalline in the presence of an external force. The latter phase change being **reversible and fully controllable** optically as well as electrically, PCM thus have an outstanding potential for active nanophotonics metadevices [10, 11]. For instance, Wang, *et al.*[10] were able to create an optically reconfigurable metasurface using spatial shaping of laser pulses to write and erase different optical functionalities in a $Ge_xSb_yTe_z$ thin films. Moreover, Rudé[12] and co-workers have demonstrated recently that such **PCM combined to plasmonic devices allows for an ultrafast** (~1ps) optical and broadband tuning of the plasmonic resonances paving the way towards the development of **ultrafast reconfigurable plasmonic nanodevices** actively controlled by light.

Although ENZ and PCM are very different materials, both shares a huge potential for future agile and ultrafast plasmonics nanodevices. As such, **actively controlling their linear and nonlinear responses by means of pulse shaping techniques will enable a new class of nanomaterials with reconfigurable properties on demand.**

In this PhD thesis, we will develop ultrafast plasmonic metasurfaces operating at telecom wavelength in which the spectral properties are tuned dynamically by **controlling the transient optical properties of ENZ and PCM substrates using pulse shaping techniques and Genetically Optimized plasmonic structures**

The PhD will be hosted mostly in the Photonics Department of ICB lab which has an extensive experience regarding the implementation of such a kind of experimental setups. We will provide the PhD student all necessary equipment to ensure the proper implementation of the project. Femtosecond laser chains and optical microscopy facilities are hosted in the Near-field Optics group. Nano-fabrication and nanocaracterization facilities are available through the ARCEN CARNOT cleanroom of the ICB lab and ENZ and PCM substrates will be provided by Dr. Pierre Noé at CEA LETI. The numerical modelling and implementation of Genetic Algorithms for the plasmonic structures will be performed by Dr. Martins at CHREA (Univ. Côte d'Azur)

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[7] Silveirinha, M. G. and N. Engheta (2007). "Theory of supercoupling, squeezing wave energy, and field confinement in narrow channels and tight bends using ε near-zero metamaterials." Physical Review B **76**(24): 245109.
[8] Alam, M. Z., et al. (2018). "Large optical nonlinearity of nanoantennas coupled to an epsilon-near-zero material." Nature Photonics **12**(2): 79.
[9] Alam, M. Z., et al. (2016). "Large optical nonlinearity of indium tin oxide in its epsilon-near-zero region." Science **352**(6287): 795-797.
[10] Wang, Q., et al. (2016). "Optically reconfigurable metasurfaces and photonic devices based on phase change materials." Nature Photonics **10**(1): 60.
[11] Raeis-Hosseini, N. and J. Rho (2017). "Metasurfaces based on phase-change material as a reconfigurable platform for multifunctional devices." Advanced Materials **10**(9): 1046.
[12] Rudé, M., et al. (2016). "Ultrafast and Broadband Tuning of Resonant Optical Nanostructures Using Phase- Change Materials." Advanced Optical Materials **4**(7): 1060-1066.