

## Epsilon-near-zero metamaterials applied to mid-infrared optoelectronic devices

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The near-zero dielectric function offers intrinsic enhancement and confinement of electromagnetic waves in highly sub-wavelength ENZ layer, thus increases light-matter interaction. In this work, we applied the ENZ concept to new structures of mid-infrared optoelectronic devices, traditionally limited by weak light-matter interaction. More precisely, we realized an ENZ electro-optical modulator (EOM) and an ENZ single-period quantum cascade detector (QCD), operating around  $10\mu\text{m}$ . The ENZ-EOM's mechanism is based on switching between strong coupling and weak coupling regimes of an ENZ mode and a cavity mode, where the ENZ mode can be tuned by electron depletion with a voltage bias. This mechanism theoretically offers a significant amplitude modulation, but has so far been little studied. As for QCD, it belongs to the family intersubband devices, generally suffers from low absorption in conventional structures, due to the selection rule. The ENZ-QCD benefits from the enhancement of electric field's normal component - the useful component for intersubband absorption.

The dielectric functions of the materials used have a central place in the optical design of these devices, so we started by carefully studying them experimentally and theoretically. The ENZ regime is reached in EOM and QCD devices, using respectively a heavily doped Drude-like InGaAs layer and a sharp intersubband transition in InGaAs/InAlAs quantum well. I carried out the optical design of the devices, followed by the microfabrication and electrical, optical characterizations.

For the ENZ-EOM device, at zero voltage bias, we experimentally observed the strong coupling regime between the ENZ mode and the cavity mode, in agreement with the optical computation. Electro-optical characterization shows a modulation depth of about 0.50-1.25dB of a large quality factor phononic mode. This modulation is comparable to the state of the art of similar devices, though it is much smaller than the simulation's value, mainly limited by a small electron density depletion (7%). This modulation demonstrated a new mechanism of three-mode coupling regime: a cavity mode, a Drude ENZ mode and a phononic ENZ mode. The phononic ENZ mode is shifted thanks to the electron density modulation in a Drude ENZ layer spatially disjoint. For future works, we plan to change for barrier material with larger band gap and to fully explore the potential of the three-mode coupling regime.

As for the ENZ-QCD, we studied the role of the depolarization shift in the dielectric function of the intersubband transition and its direct relation to the ENZ concept, allowing us to taking into account this contribution correctly. The electromagnetic computation indicates a large useful absorption in the active quantum well, up to 50-60% of the incident flux, whereas conventional QCD structure is often limited with a useful absorption of less than several percent per active period. Experimentally, optical reflectance characterization of QCD-ENZ devices at cryogenic temperature shows the intersubband transition of a single quantum well, in strong coupling regime with the cavity mode. From photocurrent and spectral response measurements, we estimate an external quantum efficiency of about 0.057% for the first generation of ENZ-QCD, about an order of magnitude below the state of the art. Considering this is the first generation of the ENZ-QCD where we encountered difficulties in the fabrication process and the theoretical modelling, the results obtained are encouraging and we believe that further improvements in next generations are realistic. The physics in the ENZ-QCD system is rich and therefore constitutes an interesting subject for future studies.